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Solar Potential Assessment: Comparison Using LiDAR Data and PVsyst

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June 2016

Student thesis, Master degree (one year), 15 HE
Energy Systems
Master Programme in Energy Systems
2015-2016

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Abstract

Energy consumption is on a permanent rise and it is becoming increasingly concentrated in cities. Hence, cities have to work on saving energy and being more efficient by finding sources with great potential to produce their own energy and implanting the correct policies. Photovoltaics is the renewable energy technology with the higher potential in the urban context and Sweden is highly committed on its investment since it is the less developed renewable source in the country.

The aim of the thesis is to compare two methodologies and determine which one is better or gives more relevant information for this kind of studies in order to evaluate how good a solar map is. For doing this, the first step is to create a solar map to have a general idea about the solar potential and to know which roofs are more suitable to install PV systems. This is made with LiDAR data using ArcGIS and SEES software. After that, another study on the quantity of solar power that could be obtained from those roofs will be performed using PVsyst, where it is possible to develop an entire PV system installation and obtain more exhaust results on energy production and shadowing. Four buildings are going to be evaluated, two public ones located in Gävle city centre (Library and Concert House) and two residential ones located in Sätra.

Factors such as the optimal tilt, the best azimuth angle and the distance between panel rows are dimensioned in order to reduce shading loss and improve the performance ratio of the system in PVsyst. The final system is defined with 10° tilt, south orientation (0° azimuth), 1.5meters distance between rows and modules in strings of 9 panels connected in series for the four buildings. The simulated production from the best alternative is compared with the solar map results. Since the solar map contains information about total yearly irradiation, the energy production is obtained by means of visual exploration of the results combined with simple calculations that include GCR and system efficiency.

The results show that a solar map is a reliable tool to obtain a general estimation of the solar potential in buildings but it is necessary to first identify its limitations and be able to filter the results. On the other hand, PVsyst software allows making several simulations and eases to obtain a PV system in a building or structure with detailed results of the system components.

It can be concluded that since the PVsyst only allows to work with specific buildings or structures, a solar map permits big amounts of data calculations. It can be said that a solar map takes part in the process of obtaining a pre-project and the PVsyst is used in the project when a real installation is sized. Nevertheless, both methods are found to be reliable and suitable for solar potential assessment works since the results obtained match.

Key words: Solar potential, Solar map, LiDAR, PVsyst.

Acknowledgements

This thesis represents not only the work to obtain an engineering master's degree, but an unforgettable experience in Sweden. I have learnt much through these years of studying and this work attempts to reflect the motivation, knowledge and interest in the topic it treats.

First, I would like to thank my thesis supervisor Mattias Gustafsson at Högskolan i Gävle. He has been encouraging me through all the problems and setbacks making me see the bright side and the possible alternatives. He has been always available whenever I have run into trouble or had a question about my research. Secondly, I would also like to acknowledge Professor Björn Karlsson, who has contributed as experienced co-supervisor giving valuable comments on this thesis.

I would also like to thank the experts who were involved in facilitating me sources of data and helping me solving problems mainly with ArcGIS software: Professor Stephan Seipel and Nancy Joy Li from the university and Audrone Jakniunaite from Gävle Energi. Without their participation and input, some of the results could not have been successfully conducted.

Finally, I must express my very profound gratitude to all of my friends here in Gävle, in particular the Spanish people, who have become a big family giving me support every single day through the thesis writing process and making me enjoy a year full of good experiences that could not have been the same without them.

And last but not least, I want to thank my parents that even being far away have provided me with unconditional support and continuous encouragement through this amazing year of study abroad. This accomplishment would not have been possible without them.

Thank you all.
Laura Pérez Amigó

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Nomenclature

AC	Alternating Current
BOS	Balance of System
CO_2	Carbon Dioxide
DC	Direct Current
DEM	Digital Elevation Model
G	Global solar radiation
GIS	Geographic Information System
LiDAR	Light Detection and Ranging
MCR	MATLAB Compiler Runtime
MPP	Maximum Power Point
PR	Performance Ratio
PV	Photovoltaics
SE	South East
SEES	Solar Energy from Existing Structures
SMHI	Swedish Meteorological and Hydrological Institute
STC	Standard Test Conditions
SVF	Sky View Factor
SW	South West
V_{oc}	Open Circuit Voltage
W_p	Watt Peak
β	Tilt angle
θ_z	Azimuth angle

1. INTRODUCTION

1.1 Motivation

Energy consumption is on a permanent rise and it is becoming increasingly concentrated in cities. Cities host about the 80% of the European population and consequently represent the 75% of the total energy demand and CO_2 emissions [1]. The European Union directive on energy efficiency in buildings (2010/31/EU) shows that buildings are responsible for consuming about 40% of the energy [2]. It is known that the reduction of energy demand and also the replacement of fossil fuels by efficient renewable energy sources has to be a priority for the future. Hence, cities have to work on saving energy and being more efficient by means of finding sources with the greatest potential to produce their own energy and implanting the correct policies to boost them.

Photovoltaics (PV) is the renewable energy technology with the highest potential in the urban context, it is versatile and does not produce any noise or pollution. Photovoltaics is ready for introduction into urban areas in several applications like multi-functional building elements, energy supply systems for public information boards, traffic control, telecommunications systems and other infrastructures [3].

Sweden's energy policy aims to create a sustainable society by promoting renewable energy and efficient energy use. The government is setting the basis for a transition from a fossil fuel based society to a sustainable energy transport and industry systems. It has adopted new energy targets by 2020 to accomplish with the European commission strategy: at least 50% of the total energy consumption should consist of renewable energy, the transport should meet a 10% and the efficiency should increase by 20% [4].

Sweden is highly committed with renewable energies. Thanks to its heavy investment in the research for alternative energy sources today they mean the 50% of the total energy share. Solar energy has been now found as the point to consider since it is easy to install and it is the less developed renewable source in the country. Even though the PV market is still limited, it has doubled its capacity four years in a row thanks to the government funding. In 2015 the total installed capacity was 79.4 MW (Figure 1) with a gross electric production of 35 GWh [5] [6].

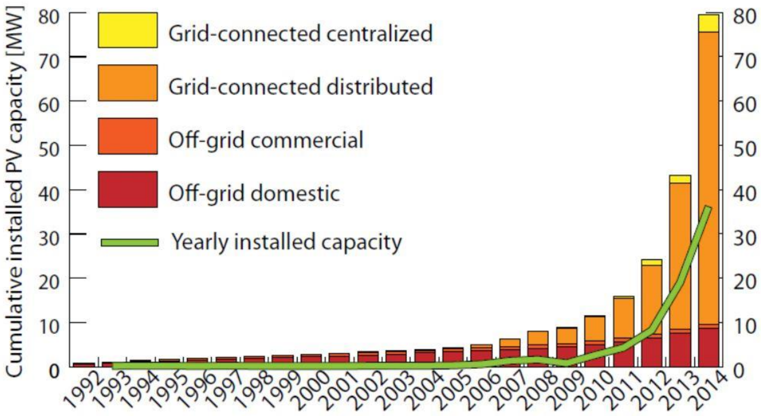

Figure 1: The cumulative installed PV power in Sweden in 4 sub-markets and the yearly installed capacity [7]

1.2 Purpose

This study has been proposed by the country administrative board of Gävle to promote the development of solar power with the idea of a future implementation. It is motivated by the fact that Sweden does an important investment in solar energy, that this idea of project can later be applied to any city or region in the world and that other Swedish cities like Stockholm, Gothenburg or Lund have already done similar research and it is found interesting to broad the knowledge in more regions.

The aim of the study is to know how much solar power the city of Gävle could get from its public buildings to promote the development of solar power. For doing this, the first step is to create a solar map to have a general idea about the solar potential and to know the roofs where it is more suitable to install PV cells. From that point, another study on the quantity of solar power that could be obtained from those more suitable buildings will be performed using a different tool. The purpose is to compare both studies and determine which one is better or gives more relevant information for this kind of studies in order to evaluate how good a solar map is.

It is accepted that the solar map will be made with ArcGIS software using point cloud data (LiDAR) already collected and available at Lantmäteriet (the Swedish National Land Survey). For the second part of the study, PVsyst software will be used in order to focus in the more interesting buildings and treat them separately.

1.3 Limitations

There are various limitations in the study to consider. First of all, due to the length and time to perform this thesis, the scope of the study has to be reduced and it is going to be focused in some representative buildings of the city of Gävle.

Also, the energy potential for the city is calculated considering PV panels on rooftops, other possible areas like facades are not taken into account. Moreover, regarding the irradiation levels, values from 2015 database will be considered which could not be exact data but acceptable for this study.

About the Solar Energy from Existing Structures (SEES) software used for creating the solar map, since it is a simplified tool to perform like ArcGIS, some features could not be as developed as desired. As for the PVsyst simulation program used, a source of error could be the created 3D models of the buildings, since the program only allows to build geometries on its database, some simplifications about the shape of the buildings have to be assumed. Moreover, a PV system as a whole is complex as there are many variables and the choice of its elements has been done considering a general PV system which could differ from the real one used.

2. THEORETICAL BACKGROUND

2.1 Solar radiation

The sun behaves as a black body at a temperature of 5777K that generates energy through fusion reactions. The solar radiation outside the earth's atmosphere is considered a constant value of G_{SC}=1367W/m^2 even though it varies from 90% to 110% approximately over the course of a year being this difference larger when larger the deviation from the equator (seen in Figure 2). This value is known as the solar constant and it is defined as the total radiation received from the Sun per unit of time per unit of area on a theoretical surface perpendicular to the Sun's rays and at Earth's mean distance from the Sun. The solar constant includes all types of solar radiation, not just the visible light.

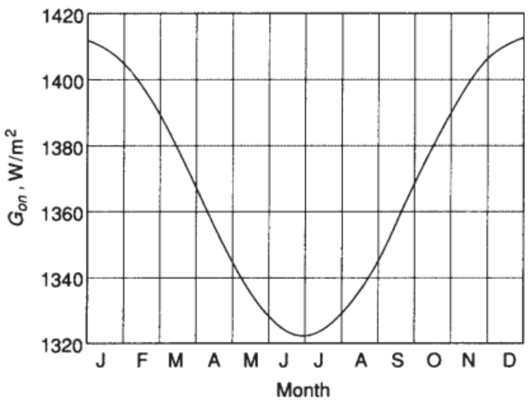

Figure 2: Variation of extraterrestrial solar radiation with time of year [8].

The solar radiation is reduced when it reaches the atmosphere. The diffuse solar radiation or sky radiation (G_d) is the one scattered that continues toward Earth with a change on its direction. The direct radiation or beam radiation (G_b) is the one that reaches the Earth in the same direction as it met the atmosphere (it is not scattered). The total radiation onto a horizontal surface on the ground, also called global solar radiation (G) is the sum of those two. For inclined surfaces, the effect of the reflected radiation (G_r) has to be also considered. [9] In the following figure, a schema of all those effects can be observed:

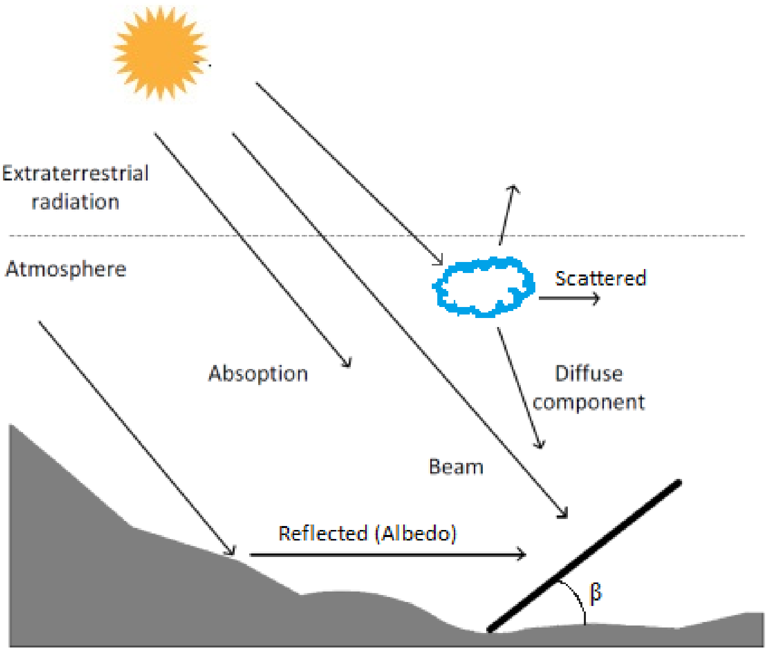

Figure 3: Solar radiation in the atmosphere

The value of the extraterrestrial radiation is the same in all the Earth's surface but since not all points on the Earth's surface are perpendicular to the Sun rays the irradiance on those horizontal surfaces is smaller because of the cosine effect illustrated in Figure 4.

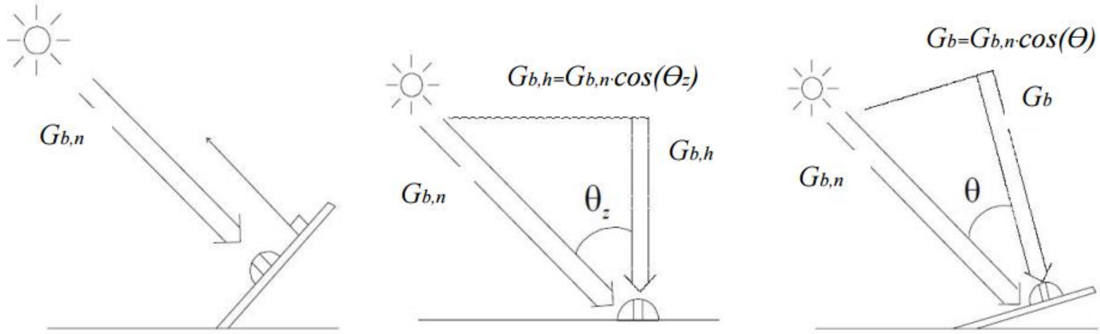

Figure 4: Left figure shows the direct radiation onto a surface perpendicular to the sun. Middle figure shows direct radiation towards horizontal surfaces. Right figure illustrates direct radiation to a tilted surface [8]

Where θ_Z is the solar zenith angle that coincides with the incident angle of the direct radiation on a horizontal surface how Lambert's cosine law states. The sub index h is for horizontal and n for normal radiation [9].

$$G = G_{b,h} + G_d = G_{b,n} * \cos(\theta_Z) + G_d \qquad (1)$$

Moreover, for a non-horizontal surface, the total irradiance depends on the incident angle to the surface (θ), the solar radiation reflected from the ground and a conversion factor for accounting the sky view factor (R) [9].

$$G = G_{b,n} * \cos(\theta) + R * G_d + G_r \qquad (2)$$

2.1.1 Global solar irradiation in Sweden

The solar irradiation depends on the weather, on the position on the globe and the season of the year. Sweden has a low average solar irradiation of 1000 kWh/m² since the maximum insolation angle is only 58 degrees in the far south [7]. Figure 5 illustrates the solar irradiation over one year in Sweden while Figure 6 shows the difference between summer and winter solar irradiation having as monthly extreme values 172 kWh/m^2 and 14 kWh/m^2 respectively.

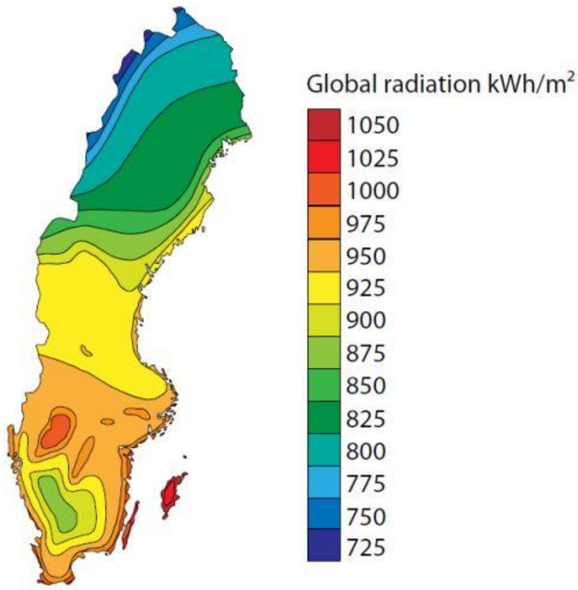

Figure 5: Global solar irradiation in Sweden in one year [7]

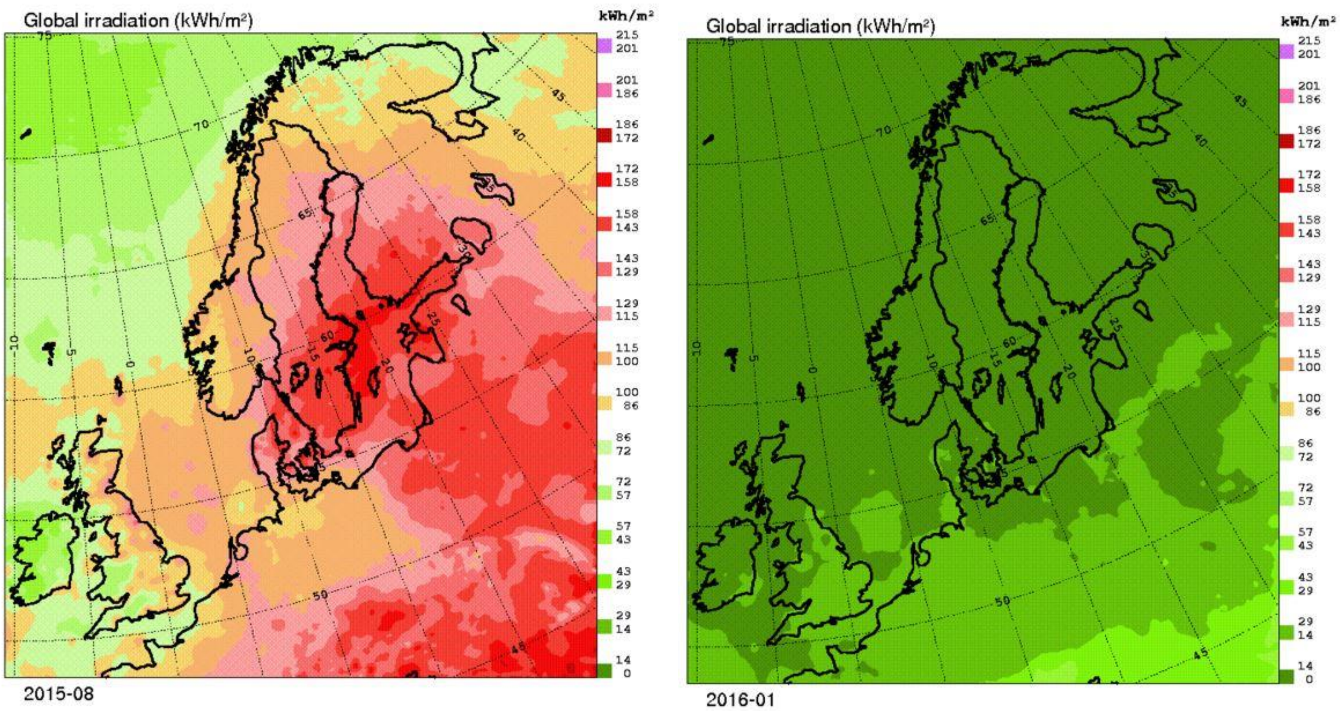

Figure 6: Global solar irradiation for a summer month (left figure) and for a winter month (right figure) [10]

In South Sweden the diffuse radiation has a higher share and yearly generation is between 700 and 800 kWh/kW$_p$. Even though, due to long daylight in summer, the yearly sums of solar electricity generation are almost the same as in the lower latitudes of Western Europe [11].

As seen in these two figures above (Figure 5 and Figure 6), the solar irradiation increases when the latitude decreases. The mean annual irradiance is highest at the latitudes of the tropics of Cancer (23.5°N) and Capricorn (23.5°S). In these locations, the sun is located with a zenith angle of 0° in the solstice (sun over the tropics) which means that it is directly situated over a possible PV module. This does not occur at the equator due to the axial tilt of the Earth.

2.2 Solar potential

The solar potential term is related to the knowledge of the total amount of energy that could be obtained from the sun. It is a task that cannot be performed manually due to its time consuming and for that it is interesting to do automated calculations. For doing those calculations data about the roofs geometry, direction and inclination is a requisite. This can be laser data from the local authority. In Sweden, the surface of PV modules mounted at the optimum angle that would be needed to satisfy the total electricity demand is about 0.37% of the country area, which means about 1666 km^2 [11].

Some studies have already been performed on that field and mostly do it by creating a solar map. A solar map is a 2D GIS (Geographic Information System) map to visualize the annual solar irradiation on building surfaces by using a colour scale accompanied by the output of solar thermal or photovoltaic systems. Depending on the detail of the information they can contain data about: annual solar irradiation (kWh/m^2), considered technologies (PV and Solar thermal), total output per roof (kWh), assumed efficiency of the technologies, building heritage, irradiation value per category (kWh/m^2) and minimum surface of solar system (m^2). Example of Swedish cities that have created one are Stockholm, Gothenburg and Lund as well as various cities from Austria, Germany, Netherlands, Portugal, Switzerland and United States [12].

2.3 Photovoltaics (PV)

PV is the direct conversion of light into DC (direct current) electricity based on the photovoltaic effect. The performance of PV solar energy is based on an electronic element called solar cell. A solar cell is a semiconductor material wafer, commonly silicon, that consists of two layers, one is of n-type material and the other is p-type material thus it makes a p-n junction. When the light radiation is absorbed by the solar cell, photons hit the semiconductor materials and cause a movement of electrons to the n-type side and holes to the p-type side of the junction which generates a voltage difference between the front and the back of the cell and a dissipation of power in the load.

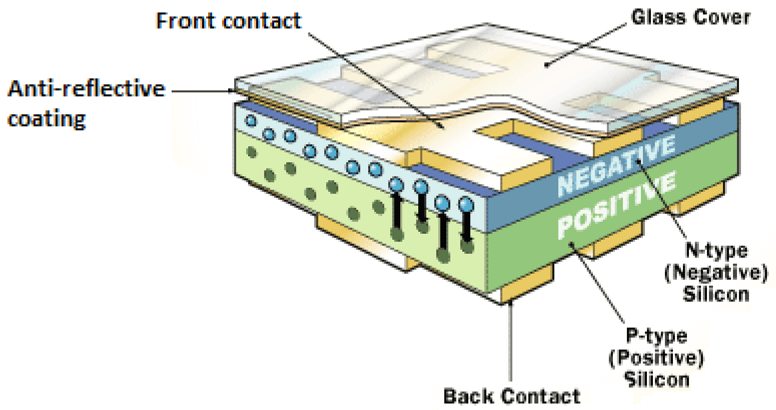

Figure 7: Schematic drawing of a silicon solar cell [13]

A typical silicon PV cell produces 0.5V and up to 3A under standard test conditions (STC) of solar irradiance 1000W/m^2 and temperature 25°C. There are various types of solar cells with different properties. Monocrystalline silicon modules are the most efficient (16%-21%) and long life ones, polycrystalline are the most common used and thin-film PV that are the cheapest but less efficient ones (7%) [14].

Several solar cells connected in series to produce higher voltage or in parallel to increase current create a module. Standard modules are made of 60 cells [14]. One or more PV modules assembled together form a PV panel and various panels together complete a PV array which is the complete power generating unit as it can be observed in Figure 8.

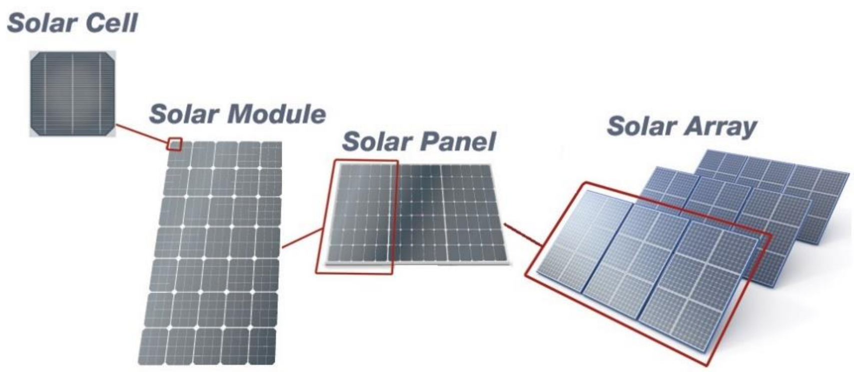

Figure 8: PV cell, module, panel and array [15]

2.3.1 Minimum roof area

There is no limitation for the minimum roof area suitable for a PV installation, however it is necessary to ensure a cost-effective installation. To decide whether a PV installation is cost-effective or not depends on the amount of energy that is produced and also the possibility to feed electricity into the grid since a tariff is obtained per kWh injected. As example, under UK conditions a minimum solar panel area of 10m^2 is required, which corresponds to an installed solar power of over 1kW$_p$ [16].

2.3.2 Orientation

It exists various options to mount the solar panels: fixed systems, tracking systems, one or two axis tracking systems, seasonal tilted modules or BIPV (Building Integrated Photovoltaics) such as roof tiles or shades. Even though, for this project it is chosen fixed tilted PV modules since the other systems have more mechanical parts, they require more maintenance and that makes them not practical for roof installations. Moreover, they are also more expensive.

The direction of a solar panel is determined by two dimensions, the azimuth (horizontal) that defines in which direction the sun is and the tilt (β, vertical) that is the inclination of the panel. As it can be seen in the following Figure 9 the best orientation is always south facing (azimuth angle of 0°). Maximum irradiation in Sweden is given in roof areas facing between SE and SW (±45° from south) and with a tilt between 20° and 55° from the horizontal plane. East and west facing panels have the problem that for either the morning or the evening, they are partially obscured. In general terms, maximum annual irradiation is given at south facing with a tilt equal to the location latitude minus 20° [17].

Inclining the PV modules from horizontal to optimum angle increases the yearly electricity production in urban areas above 16% in Scandinavia [11].

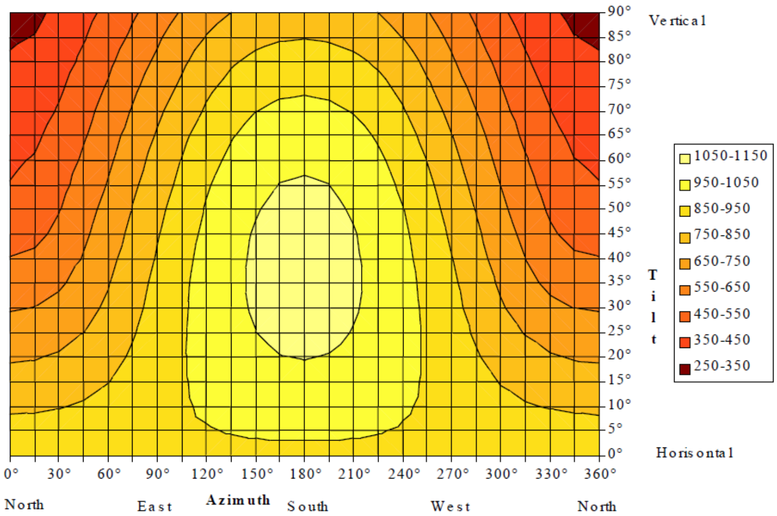

Figure 9: Total irradiation depending on different tilts and azimuth for the southern part of Sweden [17]

2.3.3 Shading

Since PV cells electricity production depends on the sun radiation they receive, when shading is produced, some negative consequences are derived. The main problem found is that the output power of the PV cell is reduced because of a decreasing current.

Furthermore, shading can produce thermal stress on the module which means that the PV circuit might reverse and if the system is not well protected, damage could happen in terms of hot spots. In the case that one cell is partially shaded, it works as a resistive load which means that it consumes electricity. The losses in the individual cell can produce high temperatures resulting in hot spots (local defects due to high temperature). In order to solve shading problems, by-pass diodes are placed connecting the cell strings in parallel. When a solar cell is reverse biased the bypass diode conducts, allowing the current from the good solar cells to flow in the external circuit rather than forward biasing each good cell [18].

Figure 10 shows the performance of an array of cells connected in series with two cases of partial shading. Case a) when two shaded cells belong to the same string and case b) when the cells belong to different strings.

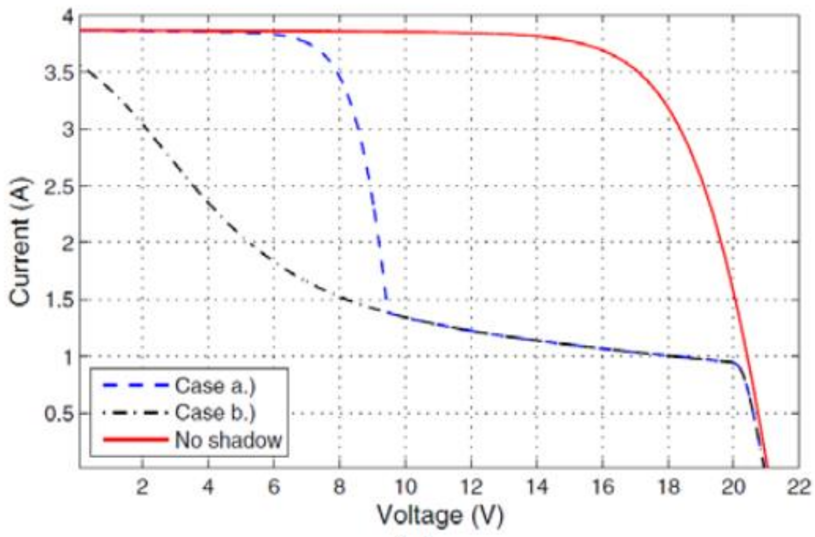

Figure 10: Characteristics of two partially shaded series-connected sub modules [19]

2.3.4 PV installation components

A grid connected PV system comprises PV modules and the BOS (Balance of System). The BOS components include the inverters, mounting systems, wiring from the array to a possible junction box, cables from the junction box to the inverter, protection and disconnection switches, the alternating current (AC) cabling from the inverter, metering and system monitoring [20].

The two main components in a grid-connected system are the modules that produce electricity from solar irradiation and the inverter, which converts the DC output to AC for matching the voltage and phase of the electricity grid.

The efficiency of a PV plant can be described by the performance ratio (PR), it presents the relationship between the actual and the specified amount of produced energy. The PR is mainly due to losses from the inverter but also resistive losses in the wiring. This relationship is expressed in percentage and shows how much of the energy that is available for export to the grid.

Another characteristic measure is the peak power (W_p), which is a normalization factor for the rating of the solar power. W_p is a term that describes the maximum power amount generated at STC.

2.3.5 Economic aspects

Over the last decade the PV market has experimented a huge expansion which has led to a significant decrease of solar modules prices by over 60% between 2005 and 2011. Solar PV module prices in 2014 were around 75% lower than at the end of 2009 and between 2010 and 2014 the total installed costs of utility-scale PV systems felt by 29% to 65% [21]. The main causes are: improved production techniques, greater competition among system developers and installers, more transparent and efficient administrative rules and grid connection procedures [22].

The economic analysis of solar PV takes into account several characteristic features. Firstly, the fuel is free and thus, the costs related to the power generation are almost zero. Secondly, increasing grid-connected solar capacity involves reducing fossil fuel generation and consequently reduce operating costs and greenhouse gases emissions. Moreover, it is a non dispatchable resource which means that its generation is variable which involves an addition of system costs for maintain the system reliability with storage and backup generation [23].

The greatest expense for a PV system is then the acquisition cost, purchase of the components and PV installation. Summing up, the total PV system costs are the sum of module costs plus the expenses for the BOS which represent the majority of the price per watt and that includes the wiring, inverter, installation, mounting, and building permit [24].

3. SOLAR MAP

This section gives an overview of the methodology followed to collect the data and achieve the aim of this report. A literature review about previous similar works has been done to know the main methods used for this kind of studies and then be able to use them for creating a solar map.

3.1 Area of study

The first step is to determine the desired area. Knowing that the data is available for all Sweden, the study is focused in the city of Gävle (Figure 11), the capital of Gävleborg country , with a surface of 42.45km^2 and a population of 71033 inhabitants. It is located at latitude 60°40N, longitude 17°8E and 3m above the sea. [25]

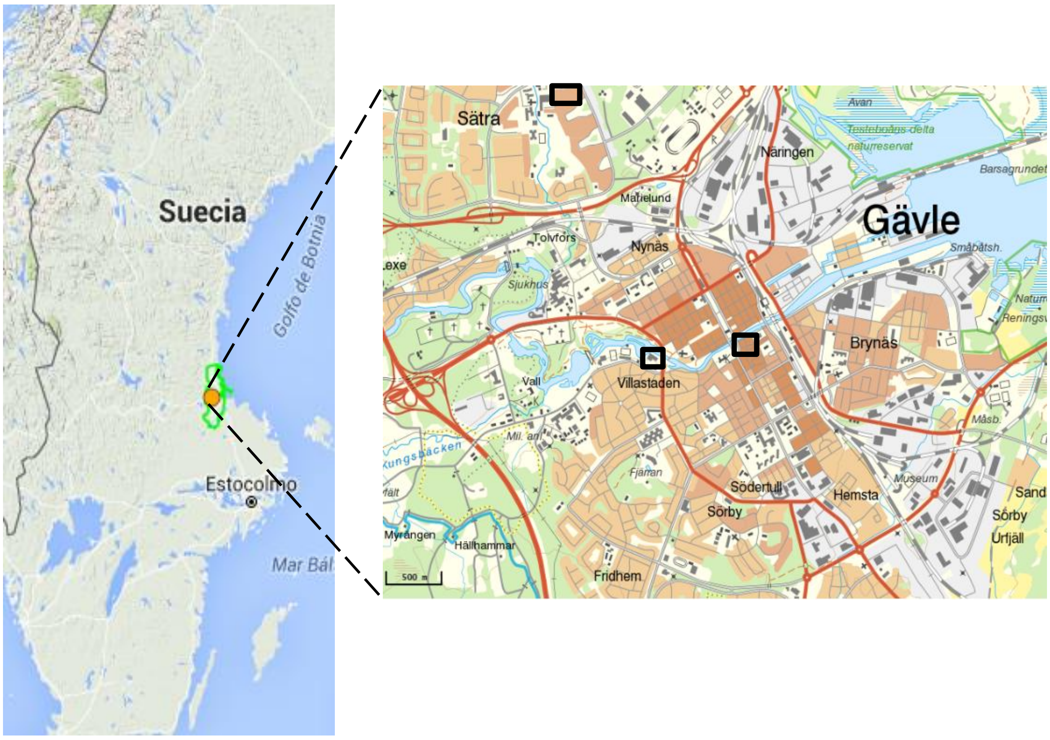

Figure 11: Situation of Gävleborg county (left) [25] and detailed area studied from the city of Gävle with the buildings of interest squared in black (right) [40]

In Gävle, the chosen buildings are two residential ones located in Sätra (a residential neighbourhood in the north of the city) and two public buildings of the city centre suitable for the installation of PV panels: the concert hall and the public library.

3.2 Light Detection and Ranging (LiDAR)

The first step to be able to create a solar map is obtaining LiDAR data. LiDAR is one of the newest available remote sensing technologies, based on active sensors, to characterize surfaces in great detail [2] [26]. It emits pulses of laser light and measures the time it takes for the reflections to be detected by the sensor. It makes it possible to obtain distances to objects and build 3D models to have the necessary detailed information about roofs (shape, tilt and direction).

The elevation data has been obtained from Lantmäteriet. Ordered by the Swedish government, they are working to produce a high accuracy National Elevation Model by airborne laser scanning method. This project started in 2009 and data from Gävle was obtained in 2015. [27]

Laser data consists of a point cloud in which each point is classified as ground, water, bridge or unclassified (which also includes incorrect points). The data used has a point density of 0.5-1 points per square metre obtained from a flying altitude of 1700-2300 metres with a scanning angle of ± 20°. The coordinate system used is in plane SWEREF 99 TM and in height RH 2000. [27]

3.3 Meteonorm

Meteorological data is also necessary to perform the study, it is obtained from Meteonorm, a meteorological database that contains worldwide weather data. The main climate parameters available are irradiation and temperature among others. Monthly climatological parameters are available for the periods 1981–1990 and solar irradiation for 1991–2010 [28].

It is possible to import the data to the photovoltaic simulation software and it is considered to be the meteorological reference for the following applications: solar energy, building design, heating and cooling systems, education and renewable energy system design [28].

Table 1: Meteonorm values for Gävle irradiation in kWh/m^2 and temperature.

	G_h	D_h	B_n	T_a
January	7	5	12	-2,7
February	19	14	25	-2,7
March	63	29	97	0
April	115	52	140	6
May	150	81	136	11,3
June	160	88	134	15,4
July	160	78	154	17,9
August	106	61	95	16,8
September	70	34	89	11,8
October	31	18	49	6,1
November	8	7	9	2,3
December	4	3	8	-1,3
Year	891	468	948	6,7

Where:
- G_h: global horizontal radiation (GHI) [kWh/m^2].
- D_h: diffuse radiation [kWh/m^2].
- B_n: direct normal radiation [kWh/m^2].
- Ta: mean daily temperature of the air [°C].

3.4 Geographic Information System (GIS)

GIS is a system that manages digital geographic information and data in different layers. It lets visualize, analyse and interpret data [29]. The available tools allow to analyse spatial information, edit data in maps and present the results.

Once the necessary data is obtained, working with it in GIS makes it possible to create a Digital Elevation Model (DEM) and obtain a solar map thanks to the available tools. Geographic information is geographically located data by using coordinates x, y and z representing longitude, latitude and elevation respectively.

3.4.1 ArcGIS

ArcGIS is a software for geographic information developed by ESRI. This thesis is done with ArcGIS 10.3.1. The ArcMap application has various tool boxes which can perform operations and calculations necessary in this study. The solar radiation analysis tools in the ArcGIS Spatial Analyst enables to analyse and map the effects of the sun over a determined geographic area for specific time periods but due to its complexity, this program will be used just to create the DEM.

Execution

The following process is the one necessary to obtain a DEM from point clouds data as starting point [30] [31]:

- Create a LAS dataset with the LiDAR data.
- Convert the LAS dataset to a continuous elevation model.
- Divide the elevation model into a grid.
- Clip the grid to obtain the area of studied buildings.

For more specific information, Appendix I contains the steps followed.

3.5 Solar Energy from Existing Structures (SEES)

SEES is a computer software model to estimate the energy potential from solar panels installed on roofs in urban areas. SEES is written in MATLAB programming language and its graphical interface is written in Java using the MCR (MATLAB Compiler Runtime) which allows to run the MATLAB programme outside its environment [32]. It will be used instead of the ArcGIS to obtain the final solar map.

The steps followed to obtain the solar map are:

- Load the DEM building model first created in ArcGIS.
- Load or make the program create the sky view factor (SVF). The SVF is a non-dimensional climatology parameter between 0 and 1 representing the fraction of visible sky over a location. 1 means that the complete sky is visible under clear conditions.
- Set the model parameters: albedo of 0.2 and limits for acceptable irradiation levels.
- Add the meteorological hourly data (acquired from [33] based on SMHI data).

3.5.1 Energy output estimation

From the SEES solar map it is obtained a scale of colours representing the yearly irradiation (kWh/m^2) for each point of the map. In order to estimate the possible energy generation on the roof studied, it is necessary to multiply the irradiation values for the total suitable area, taken into consideration the ground coverage ratio (GCR) and the efficiency of the PV system.

GCR is the area of the PV modules divided by the roof area occupied by the PV system. GCR values are below 1, often between 0.3 and 0.7 being higher when the array rows are placed closer [34].As shown in Figure 12, an increase in tilt requires more row spacing to avoid shading. As tilt increases, GCR decreases.

$$\mathrm{GCR} = \frac{\text{PV modules area } [\mathrm{m}^2]}{\text{Ground area of the array } [\mathrm{m}^2]} \tag{3}$$

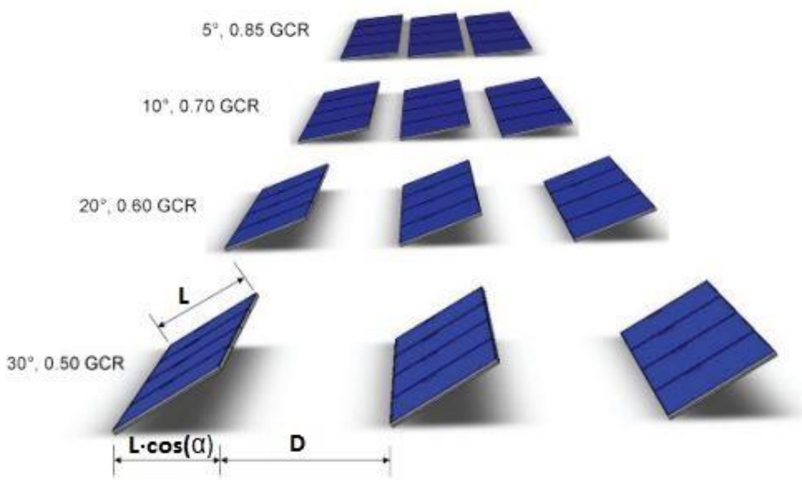

Figure 12: Comparison of GCR and tilt of the modules [35]

The calculations are made following the formula:

$$\mathrm{E_{out}} = \eta_{\mathrm{SYST}} \cdot \sum \mathrm{G_i} \cdot \mathrm{A_i} \cdot \mathrm{GCR} \qquad (4)$$

Being:

– E_{OUT} : estimated yearly energy output from the PV system [kWh].
– η_{SYST} : efficiency of the system, assumed 15%.
– i: different irradiation values.
– G_i : irradiation value for the area i.
– A_i : total area for the irradiation i.
– GCR assumed 0.3.

4. PV SIMULATION

Once the solar map is created and the results are obtained, the study is focused on the selected buildings to have a detailed analysis and be able to compare with the results.

4.1 PVsyst

PVsyst is a software used for the study, sizing and data analysis of complete PV systems (grid-connected, stand-alone, pumping or DC-grid systems). It includes extensive meteorological and PV systems components databases, as well as various solar energy tools (meteorological graphs, solar geometry parameters, irradiation models, PV-array behaviour under partial shadings, optimizing tools for orientation, voltage, etc.) [36]

The basic requirements for a study are:

- Geographical data.
- Meteorological data (imported from Meteonorm).
- Technical data (tilt and azimuth).
- 3D model of near shadings.
- PV modules design based on available roof area.
- PV system components chosen from the PVsyst database: module, inverter and strings.

An exhaustive study is possible thanks to the project design tool which aims to perform a complete system design using detailed simulations. Different system simulation runs can be performed and compared. Also a detailed economic evaluation can be performed using real component prices, additional costs and investment conditions.

4.1.1 Parameters selection

Tilt and azimuth

The system is modelled with an azimuth of 0° towards the south and with a tilt angle of 10°. To assess the tilt angles impact on produced power, the azimuth is held constant and the tilt angle is changed to 0°, 30° and 40° for simulation. Besides, the azimuth angle is also changed to east and west direction in order to evaluate its performance.

Near shading

To analyse the shading, it is necessary to first build the 3D model of the structures and its surroundings. Assuming that the considered buildings are higher than near vegetation or that they do not have any near obstacles, the only shadows considered are the ones caused by the own building shape or elements on it.

Near shadings are assumed to be linear and they are calculated through the shading factor table for the diffuse and albedo as a function of the sun altitude and the azimuth. It is calculated by interpolation during the simulation. First of all, for the given solar position, the program makes a transformation of the system coordinates to set the z axis into the sun's direction. Then, each element of the PV field is projected on the plane in order to calculate the intersection of the field element with the projection. With this, a polygon representing the global shading on the field is obtained. The shading loss factor is the ratio of the area of the shadow polygon to that of the sensitive element. This process is repeated for each sensitive field element.

Some calculations may sometimes be erroneous but in practice, this error has almost no influence on the global simulation over one year.

Shade analysis

It is possible to run a shade animation during any day of the year which will help to obtain the final layout with the less shadow possible. This simulation gives the information of the shadowing every half hour and it is possible to see shaded partial modules and also fully shaded ones which makes easier the process of changing places or removing modules.

Module choice

Various manufacturers and technologies are available to be chosen. For this thesis a monocrystalline silicon (Si-mono) module with $420W_p$ and 42V has been the one selected. The module dimensions are 1.98m length and 1.31m wide with a total area of $2.26m^2$ and a frame of 0.2m. Each module is composed of 96 cells in series.

Inverter choice

To choose the most suitable inverter it is necessary to consider the following aspects:

- The peak power of the PV array: the maximum amount of DC power that the inverter can convert to AC is usually lower than the maximum PV array power due to the losses in the system before the inverter. The output power limits how many modules can be connected to it.
- Voltage: since V is dependent on T, the values have to be checked for extreme temperatures. The V_{mpp} has to be between the inverter operating voltage limits and the V_{oc} needs to be lower than the input maximum voltage.
- Current: the number of strings in parallel cannot exceed the maximum input current of the inverter and also, the highest current of the modules has to be smaller than the maximum inverter current.
- The shading on the array: due to the amount of shading on the roof and to avoid underproduction, string inverters are the best choice.

After having considered that, the chosen inverter has a nominal AC power of 3.6kW and a minimum and maximum voltage of 350V and 700V respectively.

Row spacing

To obtain a correct module layout, it is necessary to calculate the minimum distance between arrays in order to avoid shadowing as seen in Figure 13. This is calculated with equation 5:

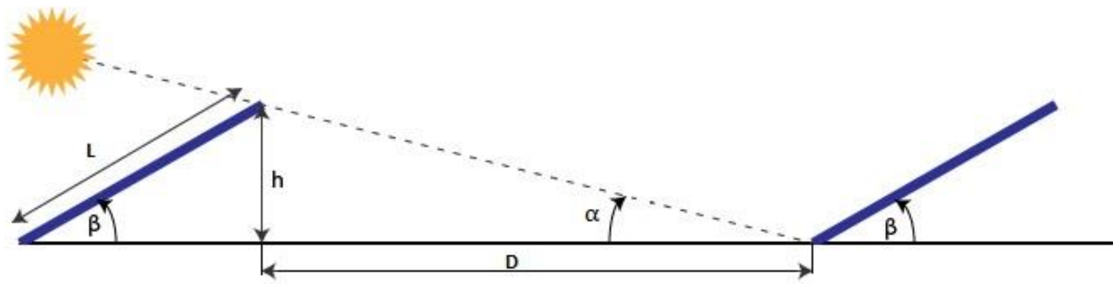

Figure 13: Parameters to calculate the minimum distance D between module rows to avoid shading

$$D = \frac{h}{\tan(\alpha)} \cdot \cos(\theta_z) = L \cdot k \qquad (5)$$

Where:

- h: height of the module depending on the tilt [m].
- α: sun altitude [°].
- θ_z: azimuth, 0° in this situation.
- L: module length, 1.7m.
- k: multiplying factor.

According to Elforsk [37], a factor k of 2.5 is obtained for estimate the distance for 30° tilt. Using the previous equation 5, for 10° tilt a k=0.868 is obtained. With the chosen modules, L=1.7m and a value of D=1.476m is obtained.

The used elements and the system characteristics are shown in Table 2.

Table 2: Specifications of the PV system elements

Element	Specification
Azimuth	0°
Tilt	0°, 10°, 30°and 40°
System type	Grid connected
Technology	Si-mono
PV module	420W_p, 42V
Inverter	3.60 kW AC, 350-700 V, 50-60 Hz

Finally, an exhaust comparison of the results from both studies is performed and conclusions are drawn.

5. RESULTS

In this section, it is exposed the process followed to find the best system for each case and simulation results for both methods used.

5.1 Solar map

The results obtained from the solar maps are shown in the next Figure 14, it can be read through the scale colour used the value of the total yearly incoming energy in every point of the selected areas.

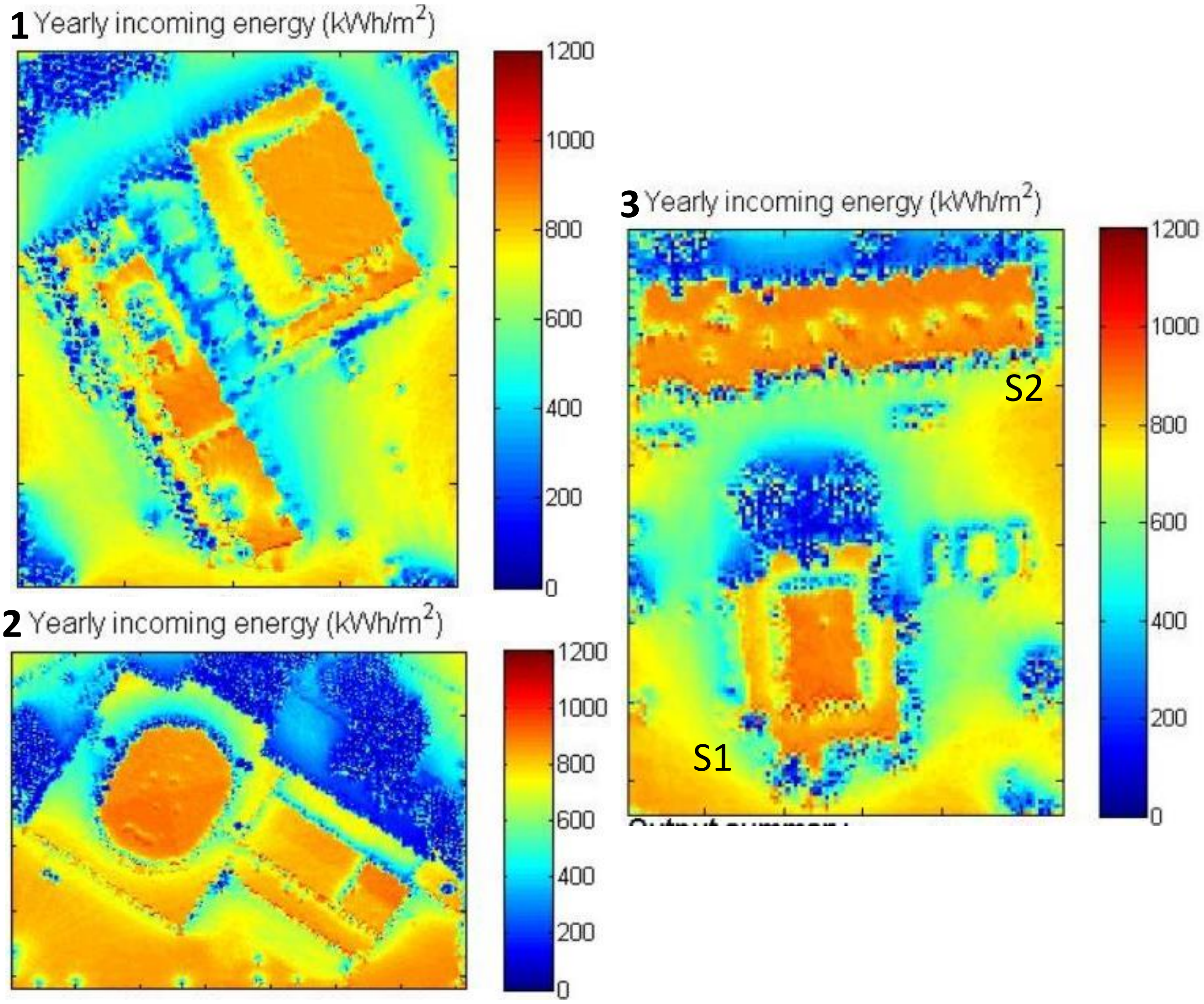

Figure 14: The resulting solar maps from the SEES software with their scale of colour. Being 1 Library, 2 Concert house and in 3, S1 Sätra building 1 and S2 Sätra building 2

Table 3 shows the estimation of energy produced in the case of installing PV systems in the roofs of those buildings. The calculations are done separately in what is considered very good, good and intermediate radiation values. The mean value of the irradiation in the areas affected is used and the yearly incoming energy under 800 kWh/m^2 is not considered.

The total roof area column accounts for the roof area extracted from the map that receives the value of irradiation written in the first column. The PV area is the estimation of the modules area that could be installed and it is obtained by multiplying the total area by the GCR. The sun radiation in modules is the radiation that is received by the area covered by modules (Irradiation x PV area) if they were ideal and the system production are the real MWh produced by a system with an efficiency of 15%.

Table 3: Results for the calculations to obtain the estimated produced energy using information extracted from the solar maps

	Irradiation [kWh/m^2]	Total roof area [m^2]	PV area [m^2]	Sun radiation in modules [MWh]	System production [MWh]
LIBRARY					
good	900	453	136	122	**27**
intermediate	800	245	74	59	
CONCERT					
very good	950	373	112	106	
good	900	474	142	128	**67**
intermediate	850	842	253	215	
SÄTRA 1					
very good	920	135	41	37	
good	850	80	24	20	**13**
intermediate	800	120	36	29	
SÄTRA 2					
very good	950	588	176	168	**25**

5.2 PVsyst

In the PVsyst, in order to simulate different scenarios and find the optimal one the parameters that have been modified are the tilt angles, the azimuth and the distance between rows.

5.2.1 Module inclination

The maximum number of modules are placed allowing a distance between rows of 1.5 meters and connected in strings of 9 modules in series. All have an azimuth of 0° and different tilt angles from horizontal to 40° have been simulated as it can be seen in Figure 15.

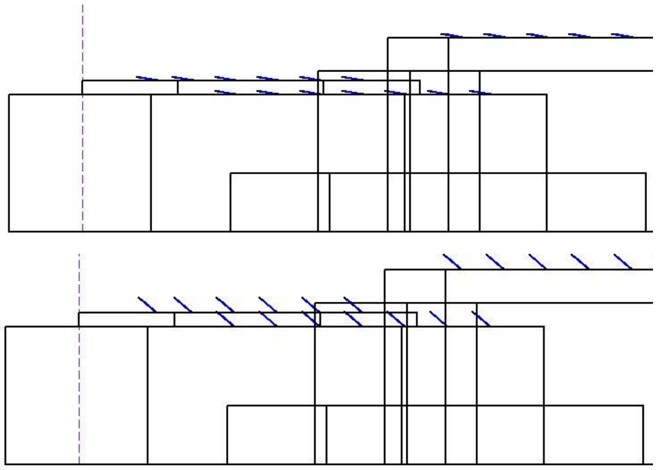

Figure 15: Tilt angles of 10° (upper image) and 40° (lower image) for the Library building

The main results are shown in Table 4 where the area shown as A refers to the active module area. The performance ratio (PR) represents the energy injected to the grid respect to the energy which would be produced by a perfect system operating at STC (the global incident radiation multiplied by the nominal installed power), it includes array and system losses. Since it is independent on the meteorological input and plane orientation it allows the comparison of the system quality between installations in different locations and orientations. The shading loss shows the percentage of the linear losses caused by near shading and the system efficiency is defined as the available energy at inverter output divided by the gross area of the system.

Table 4: Main results for the simulation with varied modules tilt angle

	Array	Tilt [°]	Produced energy [MWh/year]	Specific production [kWh/kWp/year]	PR [%]	Shading loss [%]	System efficiency [%]
LIBRARY	90 modules (10 strings) A=233m^2	0	27	714	80	-1.3	13.0
		10	29	780	80	-1.7	13.1
		30	31	812	76	-6.3	12.3
		40	31	825	75	-9.5	12.2
CONCERT HOUSE	135 modules (15 strings) A=310m^2	0	39	683	76	-5.2	12.4
		10	43	758	78	-4.3	12.7
		30	47	824	77	-7	12.4
		40	47	821	75	-9.7	12.1
SÄTRA S1	27 modules (3 strings) A=70m^2	0	7	593	66	-18	10.8
		10	8	662	69	-16.2	11.4
		30	8	703	67	-19	10.9
		40	8	700	66	-20.3	10.7
SÄTRA S2	81 modules (9 strings) A=186m^2	0	24	712	80	-1.4	12.9
		10	27	779	80	-1.7	13.0
		30	28	836	78	-5.9	12.6
		40	28	831	75	-9.8	12.2

Figure 16 shows the result of the produced energy in the four buildings for all of the tilt angle simulations:

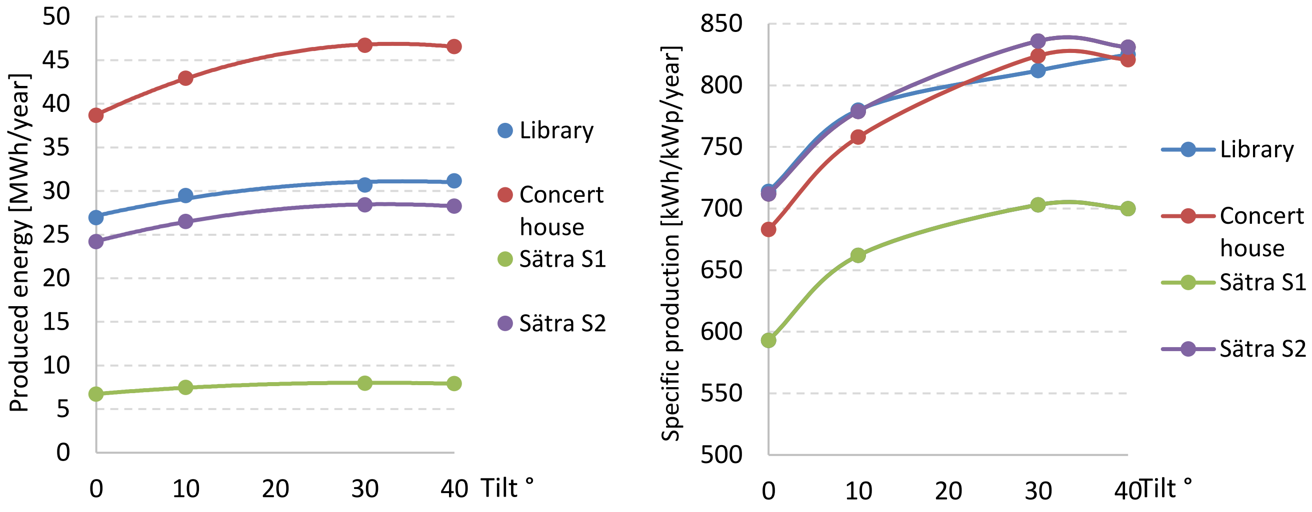

Figure 16: Produced energy and specific production depending on the tilt angle

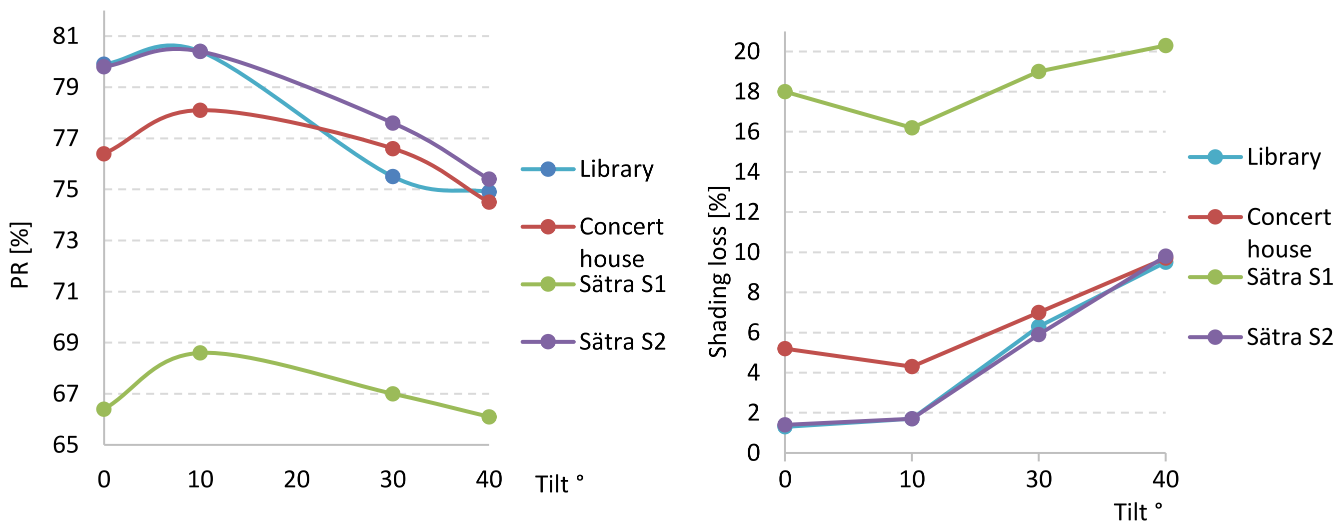

Figure 17: PR and shading loss evolution depending on the tilt angle

5.2.3 Module orientation

Another consideration in the installation of the PV modules is their orientation. All the results so far have been calculated with azimuth 0° (south facing) but in Table 5 the results for different azimuths (SW, south west facing and SE, south east) coinciding with the building orientation are presented, maintaining the 10° tilt.

Table 5: Results obtained in different azimuth angle for the modules.

	Azimuth [°]	Tilt [°]	Produced energy [MWh/year]	Specific production [kWh/kW$_p$/year]	PR [%]	Shading loss [%]	System efficiency [%]
LIBRARY	60 SW	10	28	744	80	-1.6	13
	30 SE	10	29	770	80	-2	13
CONCERT HOUSE	35 SW	10	42	747	78	-4	12.7
	55 SE	10	37	659	70	-13.6	11.4

Also, in the following Figure 18 an example of the modules placement in the two possible directions following the building shape is represented.

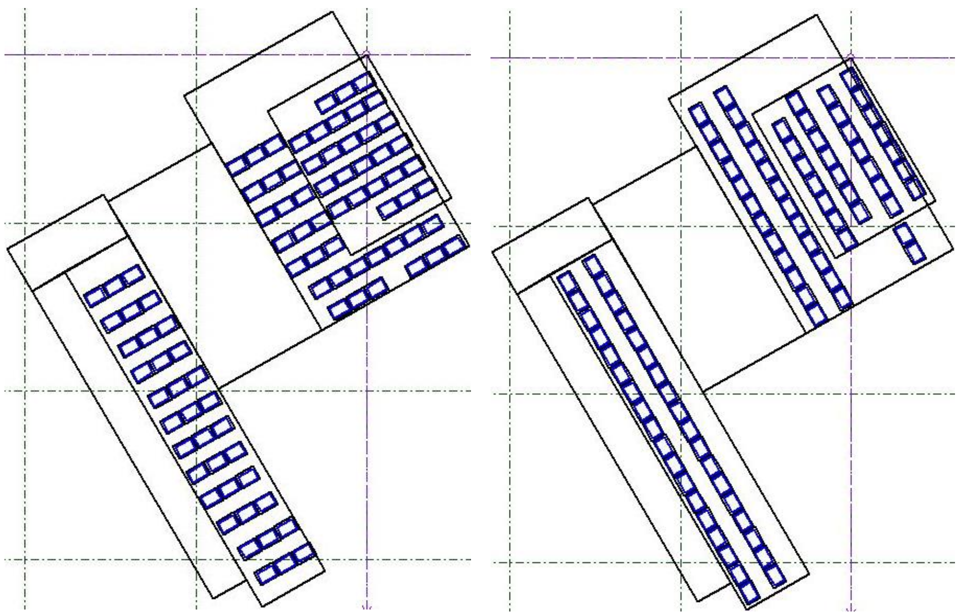

Figure 18: Modules with azimuth 30 SE (left) and 60 SW (right) in the library building

5.2.4 Space between rows

Finally, Table 6 presents the results when the distance between module rows is changed from 1.5 meters to 0.5 and 2 meters (an example is illustrated in Figure 19). The simulations are done maintaining the same number of modules.

Table 6: Results with distance between rows changed to 2 meters and 0.5 meters

		Tilt [°]	Produced energy [MWh/year]	Specific production [kWh/kW$_p$/year]	PR [%]	Shading loss [%]	System efficiency [%]
LIBRARY	2 meters distance	10	29	779	80	-1.8	13.0
		40	32	839	76	-8	12.4
CONCERT HOUSE		10	43	754	78	-4.7	12.6
		40	47	835	76	-8.2	12.3
LIBRARY	0.5 meter distance	10	29	774	80	-2.2	12.9
		40	30	781	71	-13.9	11.5
CONCERT HOUSE		10	43	752	78	-5.3	12.6
		40	44	775	70	-14.9	11.4

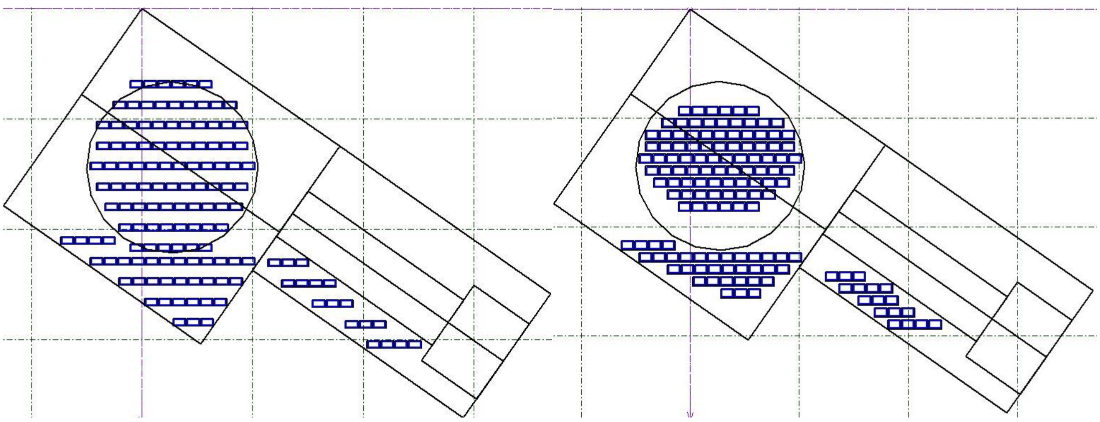

Figure 19: Example of modules layout in the concert house for 2 meters (left image) and 0.5 meters (right image)

6. DISCUSSION

6.1 Solar map

It is necessary to first highlight that the results obtained are an approximation since the radiation values are read from a colour scale (not numerical) and the affected areas are found by visual calculation. Also, for generating the visual output, building pixels are classified by SEES however, if the urban structures are complex and it is difficult to detect the building pixels in the loaded DEM, as it happens in this case, the summary of results is inaccurate and the results should be analysed with GIS by means of the ASCII files generated.

What makes the difference about the received sun radiation values for the buildings is the height of the structures and shadows caused by themselves or the surroundings. It is observed that even though the study is focused on buildings, the ground, vegetation and water (lakes, seas, rivers, etc.) are also represented in the used DEM and consequently, they are taken into account in the study which could alter some of the results. However, in the four case studies, none of those affect the results and just give more information about the scene.

It is perceived that the highest points have the highest values of irradiance but if there are some obstacles in those surfaces (like in building S2), they cause shadows and thus the irradiation received is lower. Even though, those higher surfaces are the best to place the solar modules and the maximum advantage should be taken from them. The medium height structures are also suitable and usually they have a good or intermediate value of radiation but they are more affected by shadowing from the taller structures. Lastly, the surfaces that receive an irradiation level lower than 800 kWh/m^2 have not been considered since the production starts to decrease significantly and also important shadow effects appear.

6.2 PVsyst

Considering the PVsyst simulations, it has to be stated that previous studies have showed that comparing PVsyst simulations with monitored real ones, the error in the results is less than ±5% which makes it a reliable method [38].

6.2.1 Module inclination

The results obtained for the modified tilt angles (Figure 16), from horizontal to 30° show that the energy production is always increased and only in the Library it continues the growing tendency until the 40°. In the other cases, it decreases but less than a 1% which means that the optimum inclination of the panels is between 30° and 40° and this energy reduction could be explained by adding the gain of the shading loss caused among panels. As seen in Table 4 the shading losses increase with increasing the tilt angle of the modules. This is a result of the distance between rows maintained at 1.5 meters while the module tilt is increased instead of widen it. Referring to the PR and the system efficiency, the best value is always found in the 10° tilt even though that the production is better with higher tilts. Observing the graphs in Figure 17 it can be seen that the PR and the shading loss behave inversely, when the PR decreases is because an increase in the shading loss. Considering these results and the fact that the highest economic surplus comes from systems with a tilt angle between 5 to 10 degrees [35], the best angle to proceed with the study is chosen to be the 10°.

Knowing that all roofs examined are flat, it could be considered the option of placing the modules horizontally so the GCR could increase to almost one and therefore producing more energy. This is a more expensive alternative option since more panels should be placed and from here the decision of compensate it with inclined panels. Also, another reason to maintain the tilt is that after inspecting the simulation results, it can be determined that even it could be possible to install more modules with horizontal settlement, it is not true that for a horizontal installation the production is higher per kW_p.

6.2.2 Module orientation

Once the tilt angle is defined, it is also important to determine the importance of the azimuth. Since the best theoretical option is south orientation to obtain the less shadowing problems, it could seem a good option to consider placing the panels in the building direction as seen in Figure 18. Both buildings studied let two possibilities, one with a south east and another with a south west azimuth. The case of the Sätra buildings is not studied since these are already facing south and thinking about a better configuration is not an issue.

Examining Table 5, in the case of the library, 60° SW presents a 4.5% worse result in the total energy production, a maintained PR and a slightly better shading loss (0.1% less). For 30° SW the results are also worse but differ less from to the ones obtained in the original south facing system. It is obtained an inferior 1% produced energy, the PR and efficiency almost do not vary and the shading loss is worse (0.3% more loses). Anyways, the total system efficiency is always maintained since it is reduced a 0.05% and 0.03% respectively which can be neglected.

In the concert house, the SW configuration is 35°, 25° less than in the previous case. It can be seen that even the production is a little lower (only a 1.4%), the rest of the parameters seem to show the same performance than the initial system. On the other hand, the 55° SE shows a much worse system, having a 15% less energy production and a 7.7% less of PR being all affected by the high shading loss found, a -13.6% in front of a -4.3% of the base case. Being the difference 25° more than the previous case, the results are worsened exponentially.

In terms of energy production it can be easily concluded that none of those configurations present an improved alternative. Examining the two case studies, both SW and SE orientations differ from 25° but what is surprising is that SW configuration always present a better result than a SE. As the azimuth increases in east direction, the shading losses increase much more and thus the energy production drops. In conclusion, knowing that south direction gives the best result, in case it is necessary to change its orientation it will be towards west. It could be also interesting to orientate the modules with a low angle towards west, it could improve the system efficiency as long as the PR thanks to a reduction in shading loss and it may also rise the produced energy. The energy production for east and west designs will deliver more energy during the morning and in the evening respectively. As it also has the advantage of a highest GCR, meaning that it allows installing a larger PV system on the same space, it is also remarkable to suggest a combination of both orientations for the optimization of the systems. Moreover, it seems that a low tilt is not that much influenced by the orientation. If the modules were placed with a higher tilt the discussion about the orientation should be more developed since higher differences would be found.

6.2.3 Space between rows

Regarding the simulations for changed space between rows, again only the library and the concert house are considered since the configuration of the two buildings in Sätra does not allow to make changes. It is not possible to have more space between rows due to the space available and having less space will not allow to install more modules which means that the found configuration could be taken as the optimal one. Moreover, the studied tilts are the 10° because is the most suitable one as seen before and the limit case of 40° where more extreme results could be found.

Concerning the near shadings, in this project have been considered linear ones. Another option is to simulate the real effect on the electrical production of the partially shaded strings. Although not perfect, this second approach should give an upper limit for the real shading loss evaluation but in practice it is observed that this upper limit is not so far from the lower limit (the linear loss). [36]. Moreover, by a comparison of three methods the study [39] shows that the simplifications made by PVsyst for shadow losses of diffuse radiation can be considered acceptable in view of the fact that this software performs an evaluation with simplifying assumptions, while for albedo shadow losses substantial revision is required. Anyways, as it has been said before in this thesis, even all the possible errors, the results can be accepted for the global simulation over one year.

Investigating Table 6 and comparing it with Table 4 reveals that in all the changing situations the system efficiency remains almost constant, with a maximum decrease of 0.68% in the case of 0.5 meters and tilt 40°. In both new situations the alteration of the results for tilt 10° is less than 1%. This result is coherent for 2 meters, increasing distance should improve the performance of the system or do not change it since the firstly established distance is already the minimum one necessary to avoid shadows between modules. But for 0.5 meters, since it is true that the shading losses are higher and the energy produced is lower, 240 kWh/year for the library and 320 kWh/year for the concert house, the reduction is not proportional to the decrease in distance and worse results were expected. Then it can be said that the practical minimum distance could be lower than the theoretical one which would permit to install more modules and produce more energy.

On the other hand, being the case of tilt 40° the extreme one, more differences are observed. For 2 meters distance, all the results but the total system efficiency are increased around the 2%, which means that the 1.5 meters is not enough to avoid partial shading. For 0.5 meters all the amounts are decreased from 4% to 5% which shows a significant change and clearly a wrong configuration.

Having said that, the space between rows could be reduced in order to increase the production but taking into consideration the maintenance labours, the theoretical value and the possible simulation error it is left with the initial value.

6.3 Comparison of methods

Once defined the final arrangement of the modules, it is possible to compare the results of both methods. The important results are the energy production ones but as they are narrowly related to the areas of the roofs and consequently the PV areas both comparisons are done. In Table 7 and Table 8 those values obtained in the results are summarized.

Table 7: Final values for generated energy of both methods used

	Solar map [MWh]	PVsyst [MWh]
LIBRARY	27	29
CONCERT HOUSE	67	43
SÄTRA 1	13	8
SÄTRA 2	25	27

On a first approach, the values from Table 7 seem to be reasonable. It is observed that for the library and the Sätra building 2 the result from the solar map is lower and for the other two buildings it is higher.

Analysing the library and Sätra building 2, a lower 2MWh/year of energy output is obtained in the solar map for both cases which is a difference that can be accepted as valid. It can be seen in Table 8 that the active module areas differ from 20 m^2 being this the reason of the mismatch. For both cases, the building roofs have almost rectangular shapes thus the area calculation is easy and also the radiation values are uniform in the surfaces. A possible source of error can be the differences between the GCR of the configurations (in some cases higher and in others lower) and the 0.3 value set for the solar map calculations, also the system efficiency used for the solar map calculations is a 15% and in the other cases it is lower around 13%.

Table 8: Active module area for both simulations

	Solar map [m^2]	PVsyst [m^2]
LIBRARY	210	233
CONCERT HOUSE	507	310
SÄTRA 1	101	70
SÄTRA 2	176	186

In the concert house, a higher difference of 57% is obtained in the solar map. It is caused because the map considers that the elevated rectangular surfaces (approximately 650m^2 of total roof area that means 195m^2 of PV area) are suitable areas with very good and good irradiation values but in the reality, those are inclined surfaces which are not suitable to install modules because the higher costs it will imply and also because of the shadowing problems they would cause.

In building Sätra 1 also a 73% more of energy produced is obtained. In this case, the cause is the same than in the previous one, the highest structure and furthermore the most irradiated one is a 4 sided inclined roof which in practice only the front part is profitable. Also, the surrounding surfaces have an inclination of 5 degrees and the only one totally used in the PVsyst simulation is the front one. This area difference means 31m^2 of modules area which also matches with the energy difference.

In the last two cases, the inclined surfaces are presented as highly irradiated meaning that they are not well detected by the SEES. This could mean that the inclination is not big enough to be detected or that the program considers them suitable since the modules installation is not taken into account for this software. A limitation of that kind of studies is found and the importance of a later more exhaust analysis.

7. CONCLUSIONS

It has been done a good comparison between a solar map used as an estimation of the solar potential and PVsyst as a more detailed software. The results encourage future studies and show the suitability of the two methodologies in order to obtain a good solar potential assessment.

Mainly it can be concluded that:

- A solar map is a reliable tool to obtain a general estimation of the solar potential in buildings but it is necessary to identify its limitations to obtain a good calculation.

- PVsyst software allows making several simulations and facilitates tools to find a good PV system in a building or structure. Detailed results for a PV installation are obtained.

It can be determined that since the PVsyst only allows to work with specific buildings or structures separately, a solar map permits big amounts of data calculations. Knowing the limitations of the solar map and taking them into account, valid results can be obtained for entire regions but if the objective is focused in concrete roofs or buildings this tool is not that precise and it would be better the use of the PVsyst software. PVsyst can also be used as a complement of the solar map. Also, a solar map has to be seen as a first approach of what could be obtained and a tool to boost the use of solar energy since the PVsyst works as a posterior step once it is decided to make an installation. Above all, the results have shown that both can be considered reliable methods.

For further studies, additional optimization of the solar radiation model input parameters would be beneficial as long as a reclassification of the point cloud data in order to obtain a building DEM model without the surrounding vegetation. By optimizing the input parameters more accurate results may be obtained for complex structures. Also, for a best result in the PVsyst shading simulations, it would be advisable to recalculate the losses taking into account the electrical effect since it is the weakest point of the software. Moreover, since the solar map results have been extracted from SEES, it is desirable to repeat the study with ArcGIS software to check the possible differences and validate the results.

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Appendix I: ArcGIS instructions

A. Create LAS Dataset

1) Create LAS datasets in ArcCatalog
2) Georeference to the coordinate system
    2.1) Properties
        2.1.1) XY Coordinate System: SWEREF99 (according to used data)
        2.1.2) Z Coordinate System: RH2000 (according to used data)
        2.1.3) LAS Files: Add Files
    2.2) Calculate statistics
3) Place the file in ArcMap

B. Converting LAS Datasets to Grid

Converts LAS Datasets to Raster by 0.5 * 0.5m cell size:

1) Conversion Tools To Grid: LAS Datasets to Raster
    1.1) Value Field: ELEVATION
    1.2) Interpolation Type: Binning
    1.3) Cell Type Assignment: Maximum
    1.4) Void Fill Method: Natural Neighbor
    1.5) Sample Type: CELL SIZE
    1.6) Sample Value: 0.5

C. Cut the area of interest

Cut a rectangle containing the area of interest for the study.
1) Data Management Tools – Raster – Raster Processing – Clip:
    1.1) Input raster: The created raster
    1.2) Rectangle:
        1.2.1) X Minimum and Y Minimum: the coordinates of the left inferior corner
        1.2.2) X Maximum and Y Maximum: the coordinates of the right upper corner

Appendix II: B PVsyst simulation results

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Grid-Connected System: Simulation parameters

Project :	**Project 1 gavle**				
Geographical Site		**Gävle**		**Country**	**Sweden**
Situation		Latitude	60.7°N	Longitude	17.1°E
Time defined as		Legal Time	Time zone UT+1	Altitude	3 m
		Albedo	0.50		
Meteo data :	Gävle, Synthetic Hourly data				

Simulation variant :	**library_sim_2**		
		Simulation date	12/05/16 08h38

Simulation parameters

Collector Plane Orientation		Tilt	10°	Azimuth	0°
Horizon		Free Horizon			
Near Shadings		Linear shadings			

PV Array Characteristics

PV module	Si-mono	Model	**9T6 420**		
		Manufacturer	Helios USA		
Number of PV modules		In series	9 modules	In parallel	10 strings
Total number of PV modules		Nb. modules	90	Unit Nom. Power	420 Wp
Array global power		Nominal (STC)	**37.8 kWp**	At operating cond.	34.0 kWp (50°C)
Array operating characteristics (50°C)		U mpp	407 V	I mpp	83 A
Total area		Module area	**233 m²**	Cell area	206 m²

Inverter	Model	**StecaGrid 3600**		
	Manufacturer	Steca		
Characteristics	Operating Voltage	350-700 V	Unit Nom. Power	3.60 kW AC
Inverter pack	Number of Inverter	10 units	Total Power	36.00 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	81 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.5 %
Module Mismatch Losses			Loss Fraction	2.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

User's needs : Unlimited load (grid)

PVSYST V5.74		12/05/16	Page 2/4

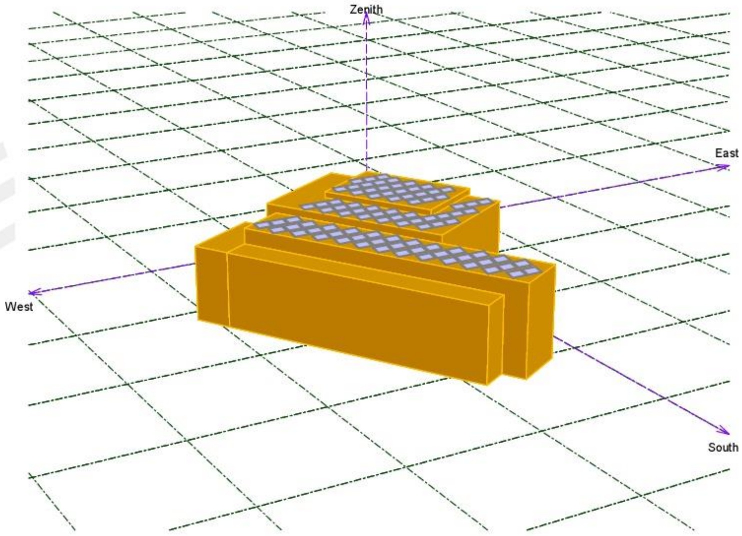
Grid-Connected System: Near shading definition

Project : **Project 1 gavle**

Simulation variant : **library_sim_2**

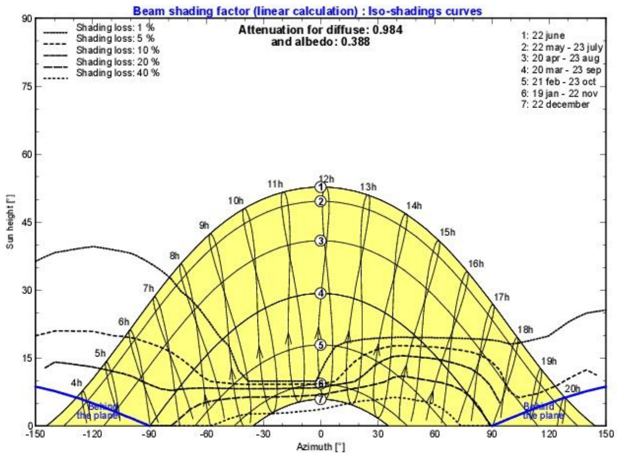
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	9T6 420	Pnom	420 Wp
PV Array	Nb. of modules	90	Pnom total	**37.8 kWp**
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	10.0	Pnom total	**36.0 kW ac**
User's needs	Unlimited load (grid)			

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram

Project 1 gavle: New shading scene



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Grid-Connected System: Main results

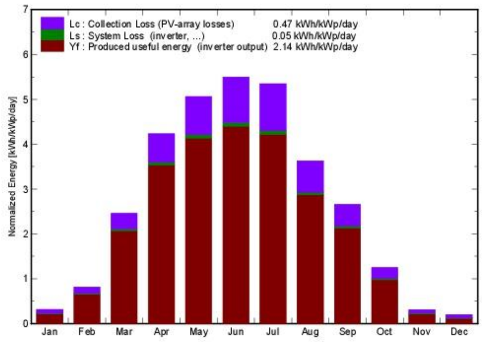
Project : **Project 1 gavle**

Simulation variant : **library_sim_2**

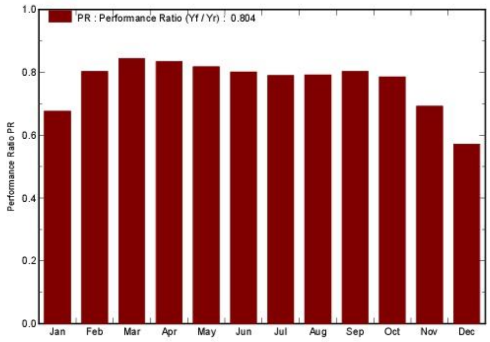
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	9T6 420	Pnom	420 Wp
PV Array	Nb. of modules	90	Pnom total	**37.8 kWp**
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	10.0	Pnom total	**36.0 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**29.49 MWh/year**	Specific prod.	780 kWh/kWp/year
	Performance Ratio PR	80.4 %		

Normalized productions (per installed kWp): Nominal power 37.8 kWp



Performance Ratio PR



library_sim_2
Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	%	%
January	7.0	-2.70	9.8	8.3	0.269	0.251	11.74	10.97
February	19.0	-2.70	22.8	20.8	0.720	0.692	13.53	13.02
March	63.0	-0.00	76.2	70.5	2.480	2.428	13.97	13.69
April	115.0	6.00	127.0	119.9	4.083	4.006	13.80	13.54
May	150.0	11.30	156.9	149.1	4.945	4.850	13.53	13.27
June	160.0	15.40	164.8	156.6	5.091	4.992	13.26	13.00
July	160.0	17.90	165.7	157.3	5.048	4.951	13.07	12.82
August	106.0	16.80	112.4	106.4	3.438	3.367	13.13	12.86
September	70.0	11.80	79.7	74.6	2.473	2.421	13.31	13.03
October	31.0	6.10	38.7	35.0	1.182	1.148	13.12	12.74
November	8.0	2.30	9.4	8.5	0.266	0.245	12.21	11.23
December	4.0	-1.30	6.3	4.9	0.148	0.136	10.15	9.28
Year	893.1	6.80	969.7	911.9	30.143	29.487	13.34	13.05

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
	GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

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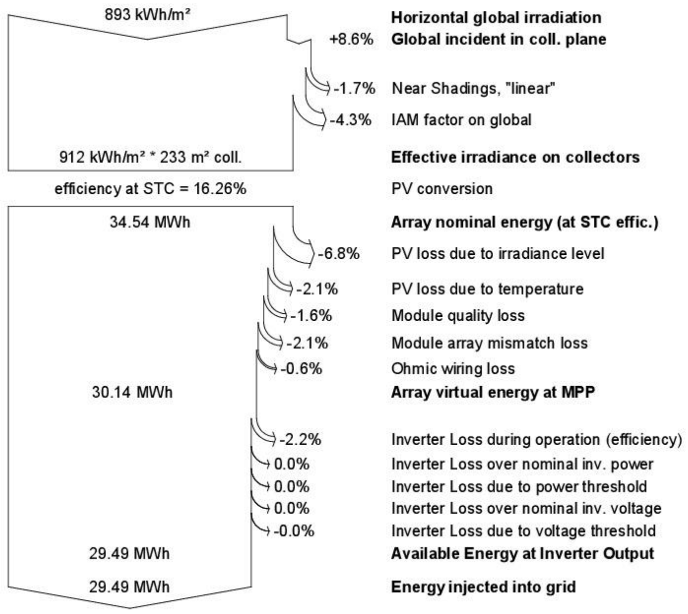
Grid-Connected System: Loss diagram

Project : **Project 1 gavle**

Simulation variant : **library_sim_2**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	9T6 420	Pnom	420 Wp
PV Array	Nb. of modules	90	Pnom total	**37.8 kWp**
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	10.0	Pnom total	**36.0 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



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Grid-Connected System: Simulation parameters

Project :	**Project 2 gavle**			
Geographical Site	**Gävle**		**Country**	**Sweden**
Situation	Latitude	60.7°N	Longitude	17.1°E
Time defined as	Legal Time	Time zone UT+1	Altitude	3 m
	Albedo	0.50		
Meteo data :	Gävle, Synthetic Hourly data			

Simulation variant :	**konsert_simulation2**			
	Simulation date	16/05/16 12h59		

Simulation parameters

Collector Plane Orientation	Tilt	10°	Azimuth	0°
Horizon	Free Horizon			
Near Shadings	Linear shadings			

PV Array Characteristics

PV module Si-mono	Model	**96M-420**		
	Manufacturer	Helios Energy Europe		
Number of PV modules	In series	9 modules	In parallel	15 strings
Total number of PV modules	Nb. modules	135	Unit Nom. Power	420 Wp
Array global power	Nominal (STC)	**56.7 kWp**	At operating cond.	50.4 kWp (50°C)
Array operating characteristics (50°C)	U mpp	399 V	I mpp	126 A
Total area	Module area	**349 m²**	Cell area	310 m²

Inverter	Model	**StecaGrid 3600**		
	Manufacturer	Steca		
Characteristics	Operating Voltage	350-700 V	Unit Nom. Power	3.60 kW AC
Inverter pack	Number of Inverter	15 units	Total Power	54.00 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	54 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.5 %
Module Mismatch Losses			Loss Fraction	2.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

User's needs : Unlimited load (grid)

PVSYST V5.74		16/05/16	Page 2/4

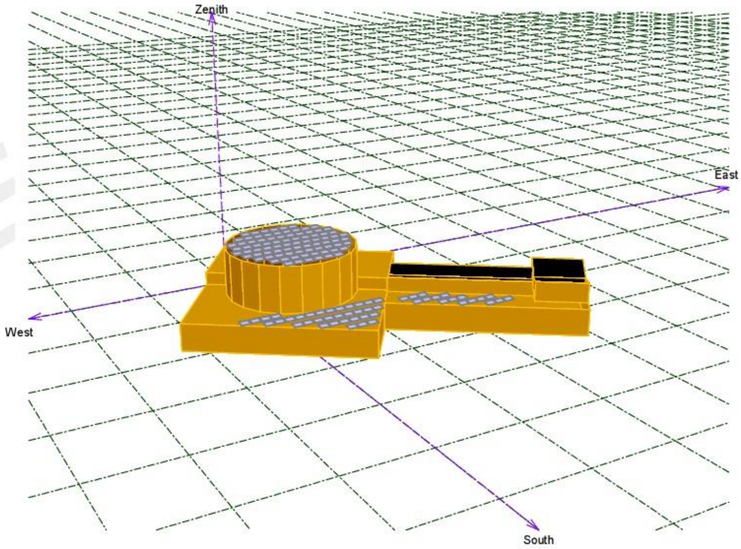
Grid-Connected System: Near shading definition

Project : **Project 2 gavle**

Simulation variant : **konsert_simulation2**

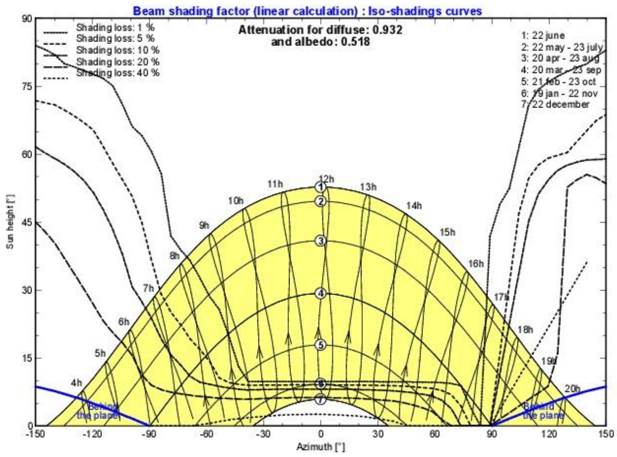
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	135	Pnom total	**56.7 kWp**
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	15.0	Pnom total	**54.0 kW ac**
User's needs	Unlimited load (grid)			

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram

Project 2 gavle: New shading scene



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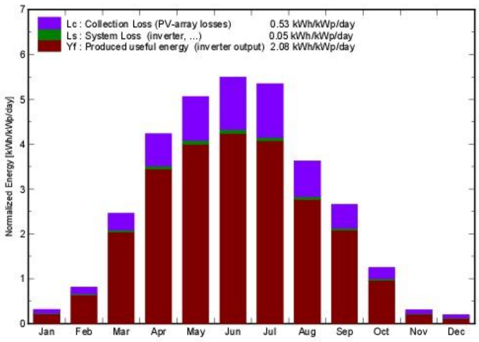
Grid-Connected System: Main results

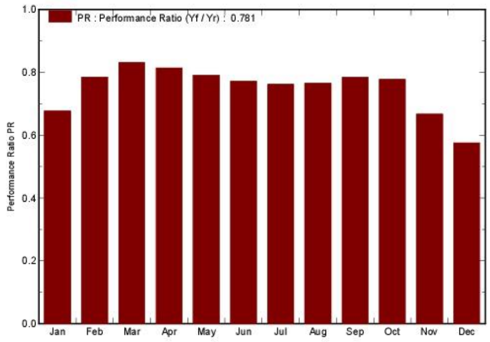
Project : **Project 2 gavle**
Simulation variant : **konsert_simulation2**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	135	Pnom total	**56.7 kWp**
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	15.0	Pnom total	**54.0 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results

System Production	**Produced Energy**	**42.96 MWh/year**	Specific prod.	758 kWh/kWp/year
	Performance Ratio PR	78.1 %		





konsert_simulation2
Balances and main results

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	EffArrR %	EffSysR %
January	7.0	-2.70	9.8	8.3	0.403	0.377	11.72	10.98
February	19.0	-2.70	22.8	20.4	1.056	1.016	13.24	12.74
March	63.0	-0.00	76.2	69.4	3.667	3.591	13.78	13.49
April	115.0	6.00	127.0	117.2	5.979	5.866	13.47	13.22
May	150.0	11.30	156.9	144.7	7.175	7.037	13.09	12.84
June	160.0	15.40	164.8	151.8	7.360	7.217	12.78	12.53
July	160.0	17.90	165.7	152.9	7.307	7.167	12.62	12.37
August	106.0	16.80	112.4	103.2	4.979	4.875	12.68	12.41
September	70.0	11.80	79.7	72.9	3.623	3.545	13.00	12.72
October	31.0	6.10	38.7	34.7	1.757	1.705	13.00	12.62
November	8.0	2.30	9.4	8.2	0.384	0.354	11.74	10.83
December	4.0	-1.30	6.3	4.9	0.223	0.205	10.16	9.34
Year	893.1	6.80	969.7	888.5	43.911	42.956	12.96	12.68

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
	GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

PVSYST V5.74		16/05/16	Page 4/4

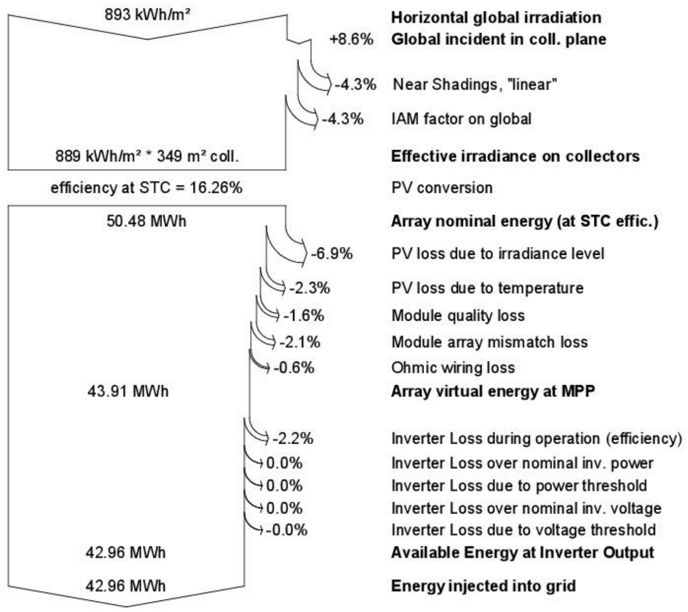
Grid-Connected System: Loss diagram

Project : **Project 2 gavle**

Simulation variant : **konsert_simulation2**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	135	Pnom total	**56.7 kWp**
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	15.0	Pnom total	**54.0 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



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Grid-Connected System: Simulation parameters

Project :	**Sätra building 1**				
Geographical Site		**Gävle**		**Country**	**Sweden**
Situation		Latitude	60.7°N	Longitude	17.2°E
Time defined as		Legal Time	Time zone UT+1	Altitude	3 m
		Albedo	0.20		
Meteo data :	Dwelling 1				

Simulation variant :	**New simulation variant**				
		Simulation date	19/05/16 13h40		

Simulation parameters					
Collector Plane Orientation		Tilt	10°	Azimuth	0°
Horizon		Free Horizon			
Near Shadings		Linear shadings			
PV Array Characteristics					
PV module	Si-mono	Model	**9T6 420**		
		Manufacturer	Helios USA		
Number of PV modules		In series	9 modules	In parallel	3 strings
Total number of PV modules		Nb. modules	27	Unit Nom. Power	420 Wp
Array global power		Nominal (STC)	**11.34 kWp**	At operating cond.	10.19 kWp (50°C)
Array operating characteristics (50°C)		U mpp	407 V	I mpp	25 A
Total area		Module area	**69.9 m²**	Cell area	61.9 m²
Inverter		Model	**StecaGrid 3600**		
		Manufacturer	Steca		
Characteristics		Operating Voltage	350-700 V	Unit Nom. Power	3.60 kW AC
Inverter pack		Number of Inverter	3 units	Total Power	10.80 kW AC
PV Array loss factors					
Thermal Loss factor		Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)				NOCT	56 °C
Wiring Ohmic Loss		Global array res.	270 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss				Loss Fraction	1.5 %
Module Mismatch Losses				Loss Fraction	2.0 % at MPP
Incidence effect, ASHRAE parametrization		IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05
User's needs :		Unlimited load (grid)			

PVSYST V5.74		19/05/16	Page 2/4

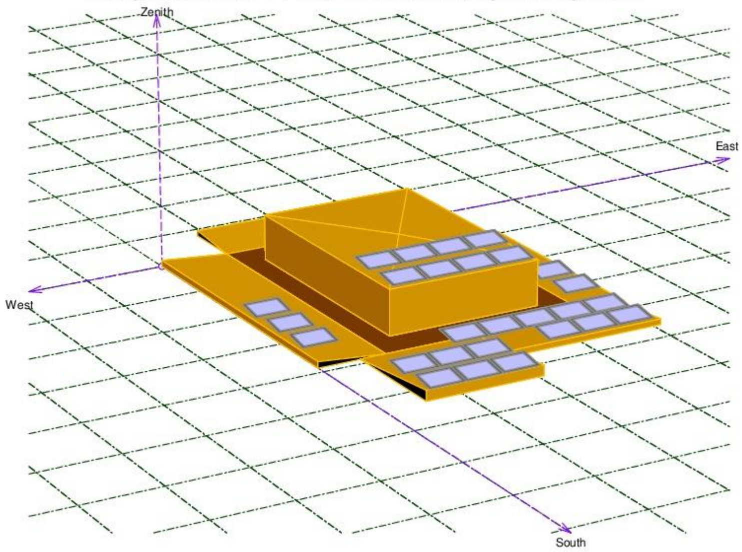
Grid-Connected System: Near shading definition

Project : **Sätra building 1**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	9T6 420	Pnom	420 Wp
PV Array	Nb. of modules	27	Pnom total	**11.34 kWp**
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	3.0	Pnom total	**10.80 kW ac**
User's needs	Unlimited load (grid)			

Perspective of the PV-field and surrounding shading scene



PVSYST V5.74		19/05/16	Page 3/4

Grid-Connected System: Main results

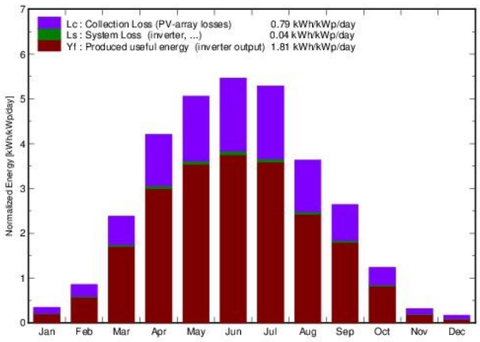
Project : **Sätra building 1**

Simulation variant : **New simulation variant**

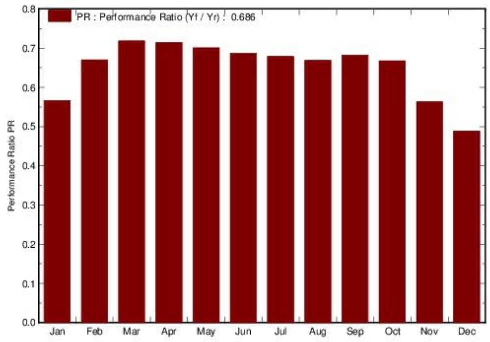
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	9T6 420	Pnom	420 Wp
PV Array	Nb. of modules	27	Pnom total	**11.34 kWp**
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	3.0	Pnom total	**10.80 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**7.50 MWh/year**	Specific prod.	662 kWh/kWp/year
	Performance Ratio PR	68.6 %		

Normalized productions (per installed kWp): Nominal power 11.34 kWp



Performance Ratio PR



New simulation variant

Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	%	%
January	7.4	-2.59	10.8	7.8	0.074	0.069	9.81	9.18
February	19.5	-3.04	23.9	18.6	0.188	0.181	11.29	10.87
March	62.5	-0.79	73.7	58.6	0.614	0.601	11.92	11.66
April	115.2	4.61	126.2	101.0	1.041	1.021	11.81	11.58
May	150.2	9.88	156.7	126.1	1.269	1.245	11.59	11.37
June	159.8	13.78	163.9	132.5	1.303	1.277	11.38	11.14
July	159.9	16.75	163.9	132.1	1.288	1.262	11.24	11.02
August	105.6	15.82	112.6	90.0	0.872	0.854	11.09	10.85
September	69.8	11.05	79.2	63.3	0.627	0.612	11.32	11.06
October	31.2	5.85	38.3	30.0	0.299	0.290	11.17	10.83
November	7.9	1.85	9.5	7.3	0.067	0.061	10.08	9.14
December	3.7	-1.31	5.2	3.8	0.032	0.029	8.96	7.93
Year	892.7	6.04	963.8	771.0	7.676	7.502	11.39	11.14

Legends:				
GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
T Amb	Ambient Temperature	E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

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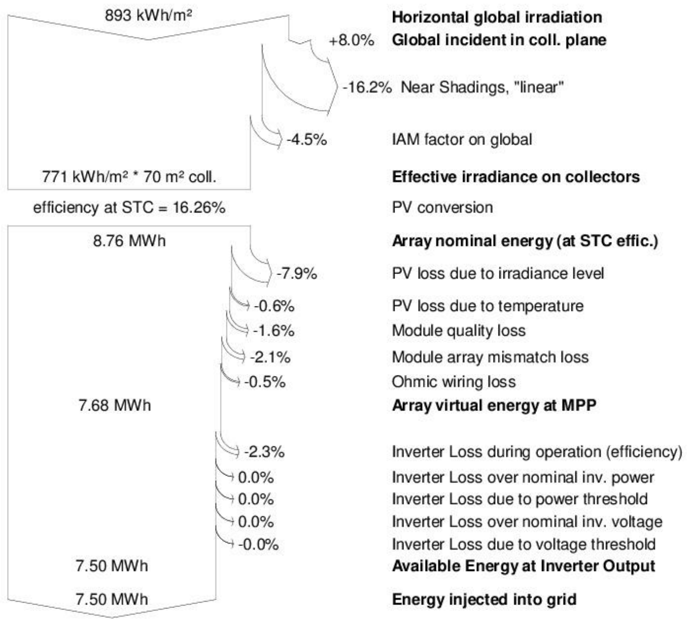
Grid-Connected System: Loss diagram

Project : **Sätra building 1**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	9T6 420	Pnom	420 Wp
PV Array	Nb. of modules	27	Pnom total	**11.34 kWp**
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	3.0	Pnom total	**10.80 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



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Grid-Connected System: Simulation parameters

Project :	**Satra building 2**			
Geographical Site	Gävle		Country	Sweden
Situation	Latitude	60.7°N	Longitude	17.1°E
Time defined as	Legal Time	Time zone UT+1	Altitude	3 m
	Albedo	0.50		
Meteo data :	Gävle, Synthetic Hourly data			

Simulation variant :	S2			
	Simulation date	19/05/16 12h46		

Simulation parameters				
Collector Plane Orientation	Tilt	10°	Azimuth	0°
Horizon	Free Horizon			
Near Shadings	Linear shadings			
PV Array Characteristics				
PV module	Si-mono Model	9T6 420		
	Manufacturer	Helios USA		
Number of PV modules	In series	9 modules	In parallel	9 strings
Total number of PV modules	Nb. modules	81	Unit Nom. Power	420 Wp
Array global power	Nominal (STC)	34.0 kWp	At operating cond.	30.6 kWp (50°C)
Array operating characteristics (50°C)	U mpp	407 V	I mpp	75 A
Total area	Module area	210 m²	Cell area	186 m²
Inverter	Model	StecaGrid 3600		
	Manufacturer	Steca		
Characteristics	Operating Voltage	350-700 V	Unit Nom. Power	3.60 kW AC
Inverter pack	Number of Inverter	9 units	Total Power	32.40 kW AC
PV Array loss factors				
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	90 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.5 %
Module Mismatch Losses			Loss Fraction	2.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05
User's needs :	Unlimited load (grid)			

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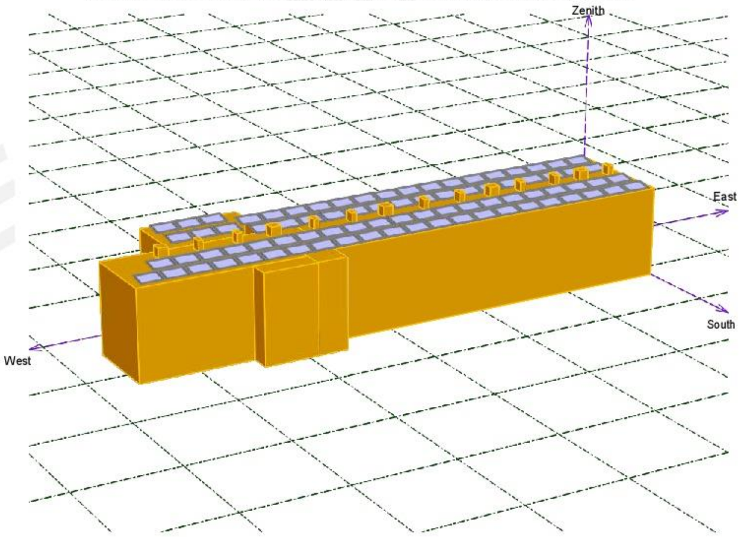
Grid-Connected System: Near shading definition

Project : **Satra building 2**

Simulation variant : S2

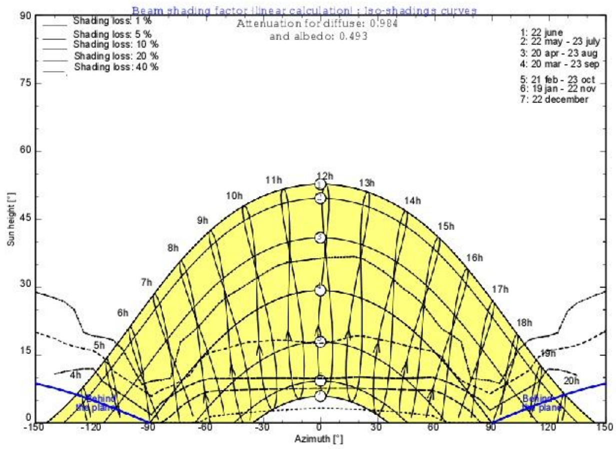
Main system parameters	System type	Grid-Connected		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	9T6 420	Pnom	420 Wp
PV Array	Nb. of modules	81	Pnom total	34.0 kWp
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	9.0	Pnom total	32.4 kW ac
User's needs	Unlimited load (grid)			

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram

Project 1 gavle: satral



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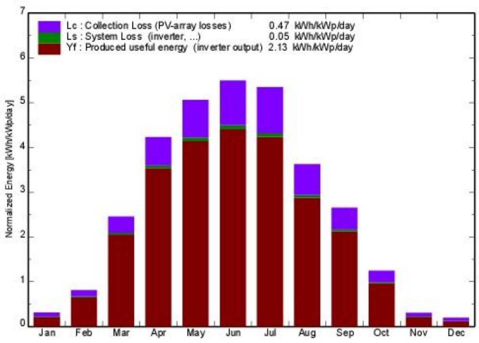
Grid-Connected System: Main results

Project : **Satra building 2**
Simulation variant : S2

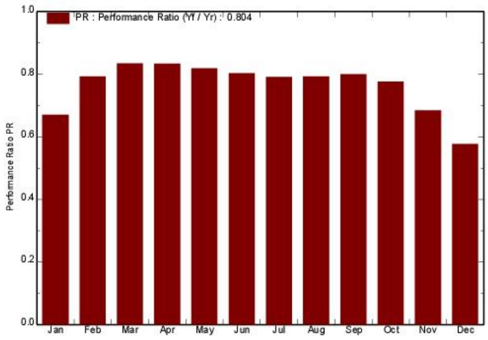
Main system parameters	System type	Grid-Connected		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	9T6 420	Pnom	420 Wp
PV Array	Nb. of modules	81	Pnom total	34.0 kWp
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	9.0	Pnom total	32.4 kW ac
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	Produced Energy	26.51 MWh/year	Specific prod.	779 kWh/kWp/year
	Performance Ratio PR	80.4 %		

Normalized productions (per installed kWp): Nominal power 34.0 kWp



Performance Ratio PR



satra1_simulation

Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	%	%
January	7.0	-2.70	9.8	8.3	0.240	0.224	11.64	10.88
February	19.0	-2.70	22.8	20.6	0.640	0.616	13.38	12.87
March	63.0	-0.00	76.2	69.8	2.208	2.162	13.83	13.54
April	115.0	6.00	127.0	119.8	3.674	3.605	13.79	13.54
May	150.0	11.30	156.9	149.3	4.456	4.371	13.55	13.29
June	160.0	15.40	164.8	156.8	4.588	4.500	13.28	13.02
July	160.0	17.90	165.7	157.6	4.551	4.464	13.10	12.85
August	106.0	16.80	112.4	106.5	3.098	3.033	13.14	12.87
September	70.0	11.80	79.7	74.3	2.217	2.171	13.26	12.98
October	31.0	6.10	38.7	34.6	1.052	1.021	12.97	12.59
November	8.0	2.30	9.4	8.4	0.237	0.218	12.10	11.11
December	4.0	-1.30	6.3	4.9	0.135	0.123	10.24	9.36
Year	893.1	6.80	969.7	910.9	27.097	26.508	13.33	13.04

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
	GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

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Grid-Connected System: Loss diagram

Project : **Satra building**

2 Simulation variant : satra1_simulation

Main system parameters	System type	Grid-Connected		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	9T6 420	Pnom	420 Wp
PV Array	Nb. of modules	81	Pnom total	34.0 kWp
Inverter	Model	StecaGrid 3600	Pnom	3600 W ac
Inverter pack	Nb. of units	9.0	Pnom total	32.4 kW ac
User's needs	Unlimited load (grid)			

Loss diagram over the whole year